# DIGITAL MAP TECHNOLOGY FOR GPS-BAED NAVIGATION AND TERRAIN AVOIDANCE SYSTEM

## FINAL PROGRESS REPORT


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**U.S. ARMY RESEARCH OFFICE**

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# A. FOREWORD

We are deeply indebted to Dr. Fancis X. Hurley from the U.S. Army Research Office for collaborating with us in the development of the GPS-Based Navigation and Terrain Avoidance System. His technical leadership ushered a monumental transformation of our vision from a novel concept into a production reality. We find that Dubbs & Severino, Inc. is experiencing more notoriety within avionics and safety circles, that our products are being fielded in greater numbers, and that more word of mouth referrals are resulting in production revenue. We have the collaboration of Dr. Hurley to thank for this success. The Terrain Avoidance innovations have been written up in more than two dozen newspapers, magazines, and web articles. These are largely the result of being a technology affiliate with the Jet Propulsion Laboratory and the international acclaim given to announcements by their NASA parent about our work.

This was a pleasant but unexpected consequence of the ARO sponsorship of us in the STTR program. We expected to get leading edge technology transferred from JPL over the course of our Phase I and Phase II efforts leading up to a fully functional prototype development. What we didn't expect is that the public relations arms of JPL and NASA have garnished us more quality contact leads since we have finished development than we can adequately respond to. In addition, Dr. Hurley's leads into both the Army program offices and to the technology plans within various organizations of the military have allowed us the best visibility towards applying our initial products to the solving real world mission needs of the services. His analysis, feedback and guidance during these last five years have helped make our small business the "success story" that the media often refers to.

For example, the leveraging of the graphics engine towards solving the problems faced by the Joint Special Operation Command could only have happened with a mature product. This is one instance of our team breaking out of the category of having just "theoretically interesting and promising designs" to instead being labeled as having field-proven, user qualified, and award winning solutions. We owe a large measure of our product maturing to our collaboration with Dr. Frank Hurley and the guidance he has given us.

We think we can be proud that our contributions to safety and situational awareness will someday save the lives of wayward navigators and their invaluable passengers.

Kimberly L. Dubbs
Robert A. Severino

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## D.1 STATEMENT OF THE PROBLEM TO BE STUDIED

The U.S. Military has a need for a covert (non-emitting) system that will assist the pilot to navigate using terrain following techniques while maintaining maximum safety against terrain impact. This project addresses the software development and system integration of a GPS-based terrain avoidance system. The system extrapolates the region immediately ahead of the aircraft and alerts the pilot when the current flight vector intercepts the safety margins surrounding upcoming terrain obstacles. The system performs its task using a set of proprietary "Adaptive Real-time Altitude Detection" (ARAD) algorithms. These compare the present GPS-derived aircraft latitude, longitude, and elevation above sea level, with the NIMA DTED data for the same location. The ARAD algorithms extrapolate ahead of the current position, giving the pilot adequate time to take evasive action in avoiding upcoming terrain. The pilot can view his current location of a laptop computer that displays topographical and military aeronautical charts, as well as photo-imagery and shaded relief depictions. The final product is called "TerrAvoid" and runs on a COTS laptop computer using the Microsoft Windows NT operating system. A companion application called "Position Integrity Tactical Display" provides essential situation awareness through the use of additional multi-window moving map graphics.

## D.2 SUMMARY OF THE MOST IMPORTANT RESULTS

The purpose of the Army Phase II STTR project was to transform the Adaptive Real Time Altitude Detection (ARAD) GPS System from the proof-of-principle prototype (which was developed during Phase I) into a deployable production system. The project has been a complete success in satisfying this objective. Not only has the system been developed, flight tested and demonstrated to the government, but it use is being adopted in avionics suites for General Aviation aircraft, in embedded military avionics packages and for demonstration use in future commercial airline cockpits. This report details the findings of our researchers in this aviation safety arena, and documents the final product as it is being used in the field.

The GPS-Based Terrain Avoidance System has been successfully developed and flight tested. It is being introduced into the aviation market in three production thrusts. A low cost version is targeted for the General Aviation segment as an option to the Position Integrity Digital Aviator software suite, soon to be available from Broad Reach Technologies for web based sale and distribution to pilots. The RTI synthetic vision effort will also usher our innovations into the GA market.

For military aircraft already equipped with older GPS equipment, we are working with a major avionics integrator to develop an add-on hardware module that will incorporate the essential functions of TerrAvoid for embedded applications.

Finally, for the commercial airline segment, NASA Ames has selected TerrAvoid to be demonstrated on board their DC-8 advanced instrumentation jet as a part of their Aviation Safety Aero Demo. This DC-8 will then be used to ferry airline executives and airframe manufacturers around the world so they can witness advanced avionics architectures in action.

In this way the innovations developed on this Army STTR phase II effort will promulgate benefits to the military, the general and the commercial aviation arenas.

In the graphics arena, the key scientific objectives of this project were to 1) use of a non-proprietary open formats like "GeoTIFF" which would maximize interoperability among the generators and users of digital maps, 2) design an architecture that would accommodate photo-imagery, shaded relief imagery, and satellite spectral imagery to complement the cartographic map datasets, and 3) find commercial sources of imagery and map sources that could be released to pilots outside of military circles. We have seen tangible evidence that these goals were all met and demonstrated to government witnesses.

## D.3 LIST OF PARTICIPATING PERSONNEL

- Kimberly L. Dubbs
- Robert A. Severino
- Dr. Kent R. Madsen
- Rich K. Fretz
- Jesse K. Lund

## D.4 DETAILS OF RESULTS

### D.4.1 AVIATION SAFETY AND CFIT

In the period from 1983 to 1994 there were 1260 Controlled Flight Into Terrain (CFIT) General Aviation (GA) accidents with 1.4 fatality per accident compared with .33 fatality per accident for all other accidents (25,273). [1] About 87% of the CFIT accidents occurred in conditions other than clear daylight Visual Meteorological Conditions (VMC). Corporate GA suffered 31 accidents in the 1984 to 1993 period.[2] CFIT accidents accounted for 40% of the accidents studied.

Of the most infamous accident examples on record, three deserve mention here. The first is American Airlines flight #965 that crashed in Cali, Columbia during December 1965. This modern 767 aircraft had a perfectly functioning Allied Signal Ground Proximity Warning System on board. Unfortunately, the system did not give the pilots a graphical view of the surrounding terrain, and did not have give adequate forward alerting to impending terrain. The system only warned the pilots 9 seconds before impact.

The second example is the T-43 CFIT accident in Dubrovnik, former Yugoslavia, which claimed the lives of Secretary of Commerce Ronald Brown also offered no modern situation awareness tools for rapid pilot visualization of surrounding terrain.

The third accident is a helicopter flight that happened in Hawaii in June 1998. The following is the NTSB summary report:

*NTSB Identification: **LAX98FA211***
*Nonscheduled 14 CFR 135 operation of OHANA AVIATION, INC. (D.B.A. OHANA HELICOPTER TOURS)*
*Accident occurred JUN-25-98 at MT. WAIALEALE, HI*
*Aircraft: Eurocopter AS-350-BA, registration: N594BK*
*Injuries: 6 Fatal.*

*On June 25, 1998, about 0930 hours Hawaiian standard time, a Eurocopter, AS-350-BA, N594BK, operated by Ohana Helicopter Tours, collided with mountainous terrain near Mt. Waialeale, Kauai, Hawaii. The helicopter was destroyed. The commercial pilot and the 5 passengers were fatally injured during the on-demand sightseeing air taxi flight which was being performed under 14 CFR 135. The flight originated from the Lihue Airport, Kauai, Hawaii, at 0843. The operator reported that the purpose of the flight was to provide the passengers with a 50 minute aerial tour of the island in accordance with a VFR company flight plan. Wreckage was observed scattered near the Waialeale crater's ridge at the 2,300 foot elevation on a 80-85 degree slope in deep foliage. The wreckage is not accessible from the ground.*

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[1] General Aviation Accidents, 1993-1994:Identification of Factors Related to Controlled-Flight-Into-Terrain (CFIT) Accidents, Volpe National Transportation Systems Center. Final Report DOT-VNTSC-FAA-97-8

[2] Khatwa, R. A.L.C. Roelen (1996) An Analysis of Controlled-flight-into-terrain (CFIT) Accidents of Commercial Operators 1988 through 1994. Flight Safety Digest 15 (4/5) 1-45.

We interviewed the NTSB Region Director Dr. Gary Mucho concerning the details of this accident. We learned the pilot was flying straight and level when he collided with the terrain at 2290 feet. The pilot was faced with rapidly rising terrain in all quadrants and had lost all situational awareness of the topography as he flew into bad weather.

We have carefully analyzed these and several other CFIT accidents and designed a terrain avoidance system that overcomes the shortfall of previous ground warning proximity systems and provides several minutes of advanced warning before possible impact. Through it visual graphics, the system show surrounding terrain a compelling and intuitive manner. (More details of the design will be described in the other reports).

This year the NASA Langley Aviation Safety Program selected a team headed up by Research Triangle Institute (RTI) to develop the next generation Low Cost Synthetic Vision System to help GA pilots avoid CFIT accidents. Dubbs & Severino, Inc. is the subcontractor on the RTI team that is providing terrain avoidance expertise and innovative technology. Together we believe our technology can help to achieve the nation goal of accident reduction. Projections by RTI show that for GA in the year 2000 a 30% reduction is possible while a 73% decrease is possible in 2020.[3] For Corporate GA a decrease of 21% is possible and a 42% reduction is possible by 2020. Our innovations will have its greatest impact in GA due to the significant projected fleet size.

## D.4.2 FAA STANDARDS

The only government organization which is working to publish standards for ground proximity warning systems, is the Federal Aviation Administration. Military programs are letting the FAA take the lead in the requirements specification arena. Several years ago the FAA approved "TSO C92c" to define the requirements and delineate operating requirements. Dubbs & Severino, Inc. was one of the evaluators of this specification and provided feedback to the FAA to improve the specification.

The last year, the FAA published a draft specification called TSO C151. This new document incorporates most of the same requirements as C92c but includes language about database accuracy, resolution and integrity.

The database components are being authored and reviewed through the RTCA Special Committee 193 (SC193), which is developing a document called "Industry Requirements for Terrain and Obstacle databases for Aeronautical Use". This Special Committee 193 is identifying, for terrain and obstacle data, :

- The requirements for data origination, publication, updating and enhancement.
- The requirements for each type of source according to the number of sources available.
- The appropriate levels of data integrity, accuracy, resolution and completeness.
- The aeronautical applications that may use terrain and obstacle databases to define database standards (e.g. TAWS, terrain display...).

RTCA SC 193 is also determining the need for a standard, generic data exchange format for terrain and obstacle databases. In addition they are co-ordinating their work with the European Organisation for Civil Aviation Equipment, Working Group 44 (EUROCAE WG 44). The results will be the combined effort of these two organisations, RTCA SC193/EUROCAE WG44.

We have made technical presentations to RTCA SC913/EUROCAE 44 in conjunction with our team-mates at the Jet Propulsion Laboratory. The topics we presented included the next generation terrain databases which will be derived from the Shuttle Radar Topography Mission (SRTM). The net effect of these presentations is that we are keeping abreast of and are contributing to the government specifications in the terrain avoidance arena.

## D.4.3 TERRAIN AVOIDANCE DISPLAY

[3] A Low Cost Synthetic Vision Display Capability for General Aviation, Research Triangle Institute, February 1, 1999.

After carefully weighing ergonomic design considerations and showing many prototype screen layouts to pilots we finally optimized a useful human machine interface for the terrain avoidance system. Two display windows are provided on the computer laptop screen. The first is a graphic window that paints an image of the terrain for an area 30 nautical miles around the aircraft in all directions. It is a box that is 1 degree by 1 degree or equivalently about 60 nautical miles on a side. Ownship is always in the center of the box and north is always up (to correspond with the north up mode in our moving map display). Terrain which is higher than the current altitude is painted red. Terrain which is from the aircraft's altitude down 500 feet (or other user selectable threshold) is painted yellow. Terrain lower than 500 feet below the aircraft is painted green. 128 shades of each color are used to give the pilot a clear graphic of the slopes of all mountains. For normal flight, a safety zone that extends 30 NM ahead of the aircraft is shown on the graphic display. Any violating terrain within the safety zone causes one of six warning modes to flag a cautionary message and sound an audible warning message (like "terrain, pull-up"). When the aircraft is landing or taking off the safety zone is reduced to 2 NM to reduce nuisance alerts.

The graphic display is 300 x 300 pixels. This window represents the terrain for 1 degree around the aircraft, which at DTED level 1 resolution, which has postings every 3 arc seconds or 100 meters. Within the window, therefore, are 1200 by 1200 postings being represented. This maps in such a way that every region of 4 by 4 DTED postings is represented by 1 color pixel. The highest value of the 16 postings determine the coloration.

With our design, not only is our data 100 times more resolute than that of our competitor Allied Signal's GPWS system, but the display is so precisely shaded that pilots can quickly grasp the slopes of the offending terrain. By comparison the Allied Signal system display is very "blocky" and only shows terrain forward of the aircraft. V-22 and helicopters need the 360-degree view that our system provides.

The second window shows text alerts for the six modes of warning, which are described in the next section. Together these screens make up the user interface for TerrAvoid.

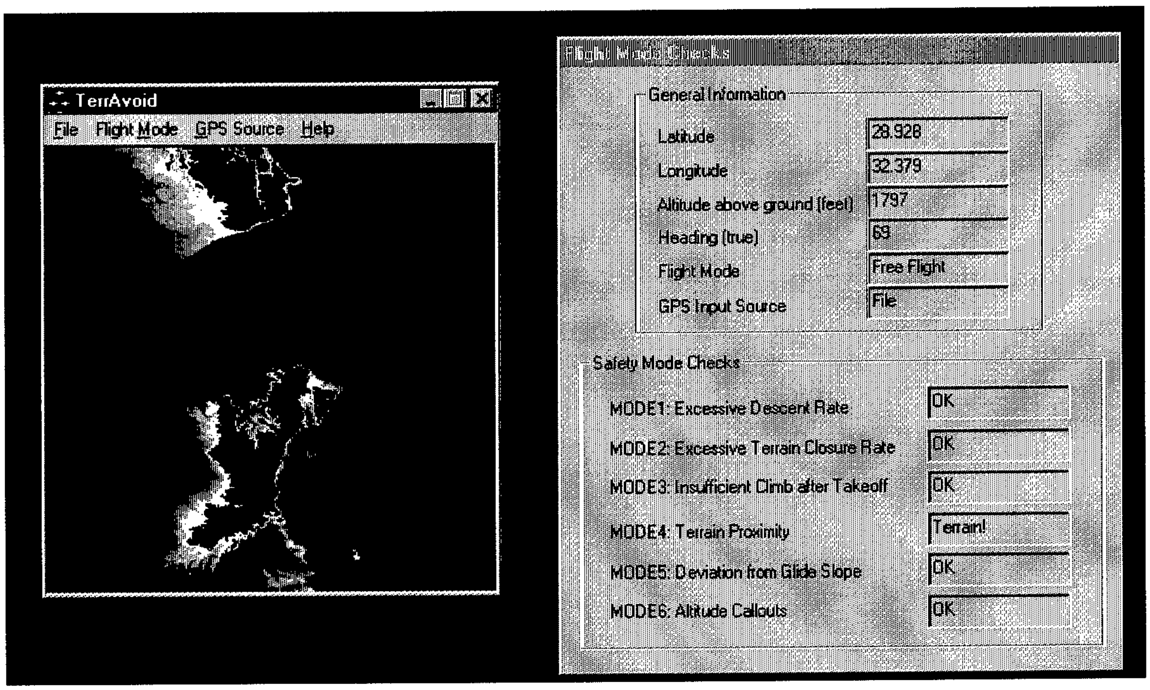



**Figure 1 TerrAvoid Window**

## D.4.4 TERRAIN WARNING MODES

For our GPS-Based Terrain Avoidance System, we used the specifications from TSO C92c and the other documents cited above. The resulting system can be broken down into six operating modes. They are listed below.

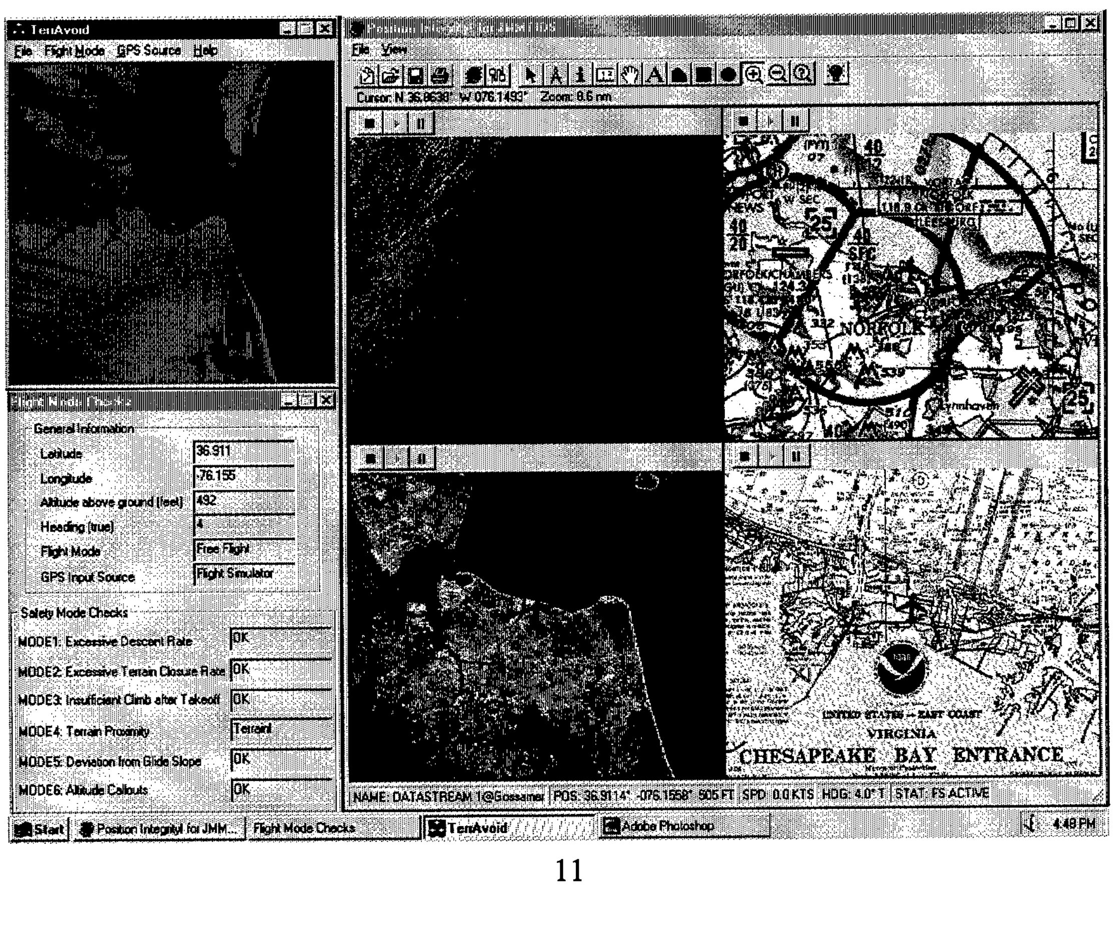
| Mode Number | Name | Purpose |
|---|---|---|
| Mode One | Excessive Descent Rate / Sinkrate Warning | To warn when the aircraft's descent rate is excessive with respect to the height above the terrain. |
| Mode Two | Excessive Closure Rate to Terrain | To warn when the aircraft is closing toward terrain at an excessive speed. This mode adds the component of speed to the normal terrain warning computations. |
| Mode Three | Excessive Descent After Takeoff | To warn when the aircraft's descent rate is excessive during takeoff or missed approach. |
| Mode Four | Insufficient Terrain Clearance | This is the "normal" operating mode for the system. It's basically the same as Mode Two, but applies to normal flight speed regime. |
| Mode Five | Inadvertent Descent Below Glideslope | To warn the pilot of "unreasonable" aircraft pitch angle during landing mode. |
| Mode Six | Altitude Callouts | To queue pilot situational awareness on landing. |

**Figure 2 TerrAvoid Warning Modes**

## D.4.5 MOVING MAP CAPABILITY

Our research shows that situational awareness for pilots is enhanced if the terrain avoidance display is augmented with a moving map display. After five years of cooperative research and development Dubbs & Severino, Inc. and Broad Reach Technologies combined forces to produce the Position Integrity tactical display system. This Windows-based multi-screen moving map software application displays all the aeronautical maps, nautical charts, shaded relief views of terrain, photo-imagery and multi-spectral imagery required by tomorrow's pilots. It accommodates both raster and vector datasets and can layer any number of these images in each window. A sample screen shot of the combined TerrAvoid and Position Integrity Tactical Display is shown below.

**Figure 3 Combined TerrAvoid and Position Integrity Displays**



## D.4.6 SYSTEM LEVEL TRADE STUDES

### D.4.6.1 Trade Study for GPS Receiver Selection

We have been in close communication with both Trimble and Rockwell, the two manufacturers of commonly used military GPS receivers. Trimble originally produced the Small Lightweight GPS Receiver (SLGR) under DOD contract and provided over 10,000 units to the military ground, ocean-going and airborne forces during Desert Storm. We have one of these units and it provided navigation signals for our Phase I flight test. Trimble has updated this product line to include the Precise Positioning Service-Security Module (PPS-SM) and Auxiliary Output Chip (AOC); together, the PPS-SM and AOC allow the receiver to decode the precise P(Y) code satellite signals. This unit, called the Centurion, is a 6 channel receiver using signals from both L1 and L2 satellite broadcasts to arrive at navigation solutions within 16 meters Circular Error Probability (CEP). The centurion has not been sold recently to DOD in large quantities.

Rockwell won the DOD contract to provide the military with large quantities of Portable Lightweight GPS Receivers (PLGRs). This unit has been updated each year since its introduction, (which has caused some intercompatibility issues with the battle commands). Version 1 was called the PLGR and was the original baseline unit which contained the PPS-SM and AOC. Version 2 was called the Enhanced PLGR or E-PLGR. PLGR-95 is the third version, which is currently available. The 4th version, called PLGR-96, will be available in April and includes new features like the ability to receive Wide Area GPS Enhancement (WAGE) which raises the positional accuracy to less than 4 meters CEP. It can also receive Differential GPS (DGPS) correction signals, while processing P(Y) code encrypted navigation. This combination is called Secure Differential GPS or SDGPS. The net effect of SDGPS is to provide navigation with less than 1 meter CEP. It can track within vehicles traveling up to 1,200 meters/sec (2683 miles per hour) and has been tested in helicopters, with no problems from propeller/ doppler reflections. All PLGRs are 5 channel receivers which receive signals on L1 only. The PLGR-96 comes in two P (Y) code versions: 1) a DOD military version which is controlled by the NAVSTAR GPS Joint Program Office out of the Los Angeles Air Force Base, CA and 2) a Federal version for use in precise positioning applications by the Army Corp of Engineers, NASA, EPA, NOAA and Departments of the Interior, Agriculture, Justice and Transportation. Both versions output navigation data in the NMEA-0183, which is a industry wide interface protocol first created for the boating and ocean shipping community. Our software will use these NMEA-0183 messages to drive the terrain avoidance software.

To date over 50,000 PLGRs have been fielded within the U.S. government and another 50,000 units have been sold to NATO forces. This large scale fielding of PLGRs, along with the success of the Centurion/SLGR during Desert Storm, have helped the military GPS community to aggregate a rich library of test reports on both units. Several government testing and research labs helped us to evaluate the Centurion versus PLGR receiver tradeoff, including Steve Deloach and Dan Oimoen from the Army's Topographic Engineering Center.

We decided to use the Rockwell PLGR GPS receiver on this contract. We considered commercial C/A code receivers which are being used in the general aviation arena, like the Trimble SV-SIX or the Motorola VP Oncore. We also considered several other military GPS receivers from Trimble like the Centurion, MUGR, Soldier and Force GPS. The following represents our thoughts on why the PLGR is the best choice for our system. The commercial units used in general aviation are limited to C/A code vertical accuracies of $\pm$ 140 meters, for a CEP of about 1000 feet. In the commercial arena, vertical positioning is usually augmented with baro-altimeters, radar altimeters, or Mode "C" 8-bit altitude encoders. None of these augmentations have the digital reliability and repeatability of digital GPS circuitry. The use of Differential GPS has been suggested for U.S. general aviation, but this is not yet an option available for worldwide military operations.

We debated if military pilots really need any better vertical accuracy than provided for the general aviation arena, when we are providing 20 nautical miles of look-ahead safety zone warning. The key driver for vertical accuracy seems to be military tilt-rotor and helicopter pilots flying on missions below 1000 feet AGL. For this class of user, a C/A code based terrain avoidance system would generate many nuisance alerts. The PLGR with P (Y) code and WAGE has a CEP of about 4 meters, and should trigger no nuisance alerts based on position inaccuracies. We have heard Vice President Gore decree that Selective Availability will be turned off between the year 2000 and 2006, but this time horizon is too far away for considering accurate C/A

code positioning (without differential) in this decade. The second factor is the potential for sales of our system to Navy commands for a Phase III production contract. The GPS Joint Program Office has already distributed over 100,000 PLGRs to military forces around the world. Rockwell is producing 120 units a day, with most future production slated for the military. We think the chances of selling a Phase III production contract to an military fixed or rotary wing command is higher if our software interfaces with the PLGR. While some military commands have the Trimble Centurion, MUGR or Force GPS, most have PLGRs. Due to production efficiencies, the PLGR costs about half of the Trimble P code units. When we deliver our system, as many as a quarter million PLGR units will be fielded worldwide to DOD and NATO forces.

We asked GPS users in the military about the limitation of the PLGR only receiving L1 and not L1 and L2 as the Trimble units do. They responded that the dual frequency capability allows the Trimble to better calculate the ionospheric correction, since signals arrive at both 1.2 and 1.5 GHz. This advantage is equaled in the PLGR, however, which accommodates the new Wide Area GPS Enhancement (WAGE), in which the ionospheric correction is now placed within the P(Y) code data stream downlinked from the satellites.

We have obtained and reviewed the PLGR Communication C Library from Rockwell and used this library to help us to develop our interface software.

Rockwell informed us that the specific model PLGR we received is the PLGR-96 (DOD/JPO version). This model has several enhanced features over the previous versions. Fortunately the basic position/navigation interface provided by the C library is compatible with the entire PLGR lineage (PLGR, E-PLGR, PLGR-95, and PLGR-96). There will also be a PLGR-96 "Federal Version" for non-DOD government agencies, a "V'PLGR-96" which has a form factor more suitable for mounting in ground vehicles, and a "Hunter" version, which has a PCMCIA form factor for laptop computers. (One drawback to the Hunter version is that its 250 milliamp requirement will drain a laptop's battery in a short period.) All the members of the PLGR family adhere to the GPS-153 interface specification, and so our software will be backwards and forwards compatible with fielded units from 1993 through at least 1998, when the Rockwell contract is up for renewal.

We also bought and flight tested the Rockwell Special Operations Lightweight GPS Receiver (SOLGR), which is also called the PLGR II. While the unit worked well for us during all the tests, the production of this unit was terminated by the U.S. SOCOM so that it will not be available to the U.S. military organizations. A modified version of the SOLGR was sold to the United Kingdom.

A GPS interface definition was generated which defines the specific way in which terrain software modules makes calls to get GPS information. It is generally considered poor design to embed GPS vendor specific commands within a software module. If this is done, then a different software version is needed every time a new hardware item changes in revision (or if another GPS vendor's receiver is used at a later date.) The approach we have taken is to create an object module library to perform all interface functions. One of the object modules in our library will be a group of routines to get GPS data from the hardware receiver. Routines were generated to get the following information about the aircraft:

1) latitude
2) longitude
3) altitude
4) heading
5) track
6) elevation angle
7) horizontal speed
8) vertical speed
9) time
10) GPS status

These routines were coded in an object oriented high level language like C++. As any other terrain avoidance software routine needs any GPS data, an "library" call is made, which invokes one the GPS object modules listed above. In this way, the other modules are uncoupled and cleanly interfaced with the object library. If the vendor's hardware changes, updates need only be made to the object library, and not to an indeterminate number of routines scattered throughout the software as would be the case without the use of the object library. Configuration control is vastly improved and portability among hardware platforms is enhanced.

During the past two years we had several meetings and conversations with Dr. Thomas Yunck, Deputy Section Manager for the Tracking Systems Research Section at JPL on the topic of space based differential GPS. We are investigating the possibility of getting sub-meter positioning accuracy without the use of authorized crypto keys through the use of JPL-developed algorithms which precisely model the GPS satellite orbits, ionospheric delay and tropospheric corrections. The advantages of a space-based architecture are that it is globally deployable and there is no need for DGPS earth reference stations. The net effect of this research on our project would be the use of terrain avoidance system in the commercial world with high navigation precision without the use of the authorized P(Y) code military signals, which of course are not available to civilians. In addition there may be military commanders who do not wish to acquire military receivers or do not want the burden of managing crypto-keys in the field. While cost for hardware implementations of the JPL algorithms are still expensive (about $5K), commercial acceptance and civil production should drive this cost down in the near future.

Although our approach to terrain avoidance centers on the look-ahead "above ground level" (or AGL) altitude, the algorithm is actually more sensitive to the aircraft latitude and longitude than it is to altitude. We therefore designed the routine to read four of the output formats (called "sentences") from the Rockwell PLGR GPS unit that deal with latitude and longitude (the horizontal component), even though one set is sufficient. Our thinking in incorporating this "quadruple redundancy" is that if anything happens in the GPS receiver to inadvertently alter one of the horizontal messages, then three others are still available for use. Although the system cannot yet automatically reconfigure itself, this is an easy mode change, which allows a great deal of robustness in our implementation. Also, if an interface to another GPS hardware unit is needed in the future, we are more likely to have the message handler in our software library, since we now can be triggered from all of the standard GPS output sentences.

The GPS interface now has the capability to update both moving map display and the terrain avoidance module simultaneously at 1Hz. Our design architecture also allows networked programs to also access the GPS data in real time and access it simultaneously with the existing two programs. For example a third program, like a recording function, was added to capture the raw GPS data for later playback in a mission debrief. (This was a limitation on our Phase I flight test, which required us to have as many GPS units as we had software programs that needed GPS data.) Our design also allows GPS data to be input on any of the computer's serial input ports for greater user flexibility.

### D.4.6.2 Trade Study for Computer Selection

Over 60 manufacturers of computers have been surveyed for determining the suitability of their platforms on this project. The technical parameters of consideration are processor chip, clock rate, RAM expansion, disk capacity, capability for CD-ROM, number and type of PCMCIA slots, battery technology, display quality (size, resolution, number of colors and brightness), keyboard and pointer interface design.

We have limited our scope of computer selection from over 70 providers to two, IBM and Toshiba. These units are superior to the other units in processor speed, PCI bus architecture, video display bandwidth, CD-ROM capability, hard disk size, RAM expansion, display size and brightness, and availability of third party PCMCIA options. Both companies have Pentium models featuring 166 MHz clock rates, which will run our Windows NT-based terrain avoidance application with real-time cycle rates.

Our JPL teammates have taken delivery of an IBM Thinkpad 760 laptop computer, which has been fully loaded with all the features desired for high-throughput portable computing. This unit helped us in a three important ways: 1) It will helped us evaluate the IBM Thinkpad as a candidate for our prototype delivery, 2) It allowed JPL to view their map databases on the same screen size, resolution and color depth before they ship the datasets to us for use in our integration testing, and 3) It served as an additional portable platform during our ground and flight tests.

Due to slightly better performance we have chosen the Toshiba Tecra laptop over the IBM. While the JPL unit came with Windows 95 installed, the NT 4.0 operating system was installed to match our desired final delivery configuration. The 4.0 shell update release (SUR) includes the same "look and feel" as Windows 95 so that users will interact with all the program features in a mostly identical way to what they are used to. We worked with JPL to do performance benchmarking with several programs running in the "preemptive multitasking" mode. This gave us the timing insight needed to partition the CPU processing power across the different applications. For example, one window might be dedicated to terrain warnings,

while a second has moving map display; a third might show imagery, and GPS status messages displayed in a fourth. Since each task requires a different amount of CPU time, RAM allocation, hard disk access and display update rate, we need a good understanding of the factors which drive the management of the multitasking environment.

It should be noted that true multitasking is one of the key advantages of Windows NT over 95. Others pluses are its more robust file system and better tools for application development. Seagull Technology, Inc., one of our commercial partners, has been running NT 3.5 on laptops for the last six months and is another source of experience-born insights for this project. While NT 4.0 does not yet feature power management for laptops currently in 95, Microsoft Windows 2000 to be released later in the fall should include this useful NT patch for conserving laptop battery time. The "Plug and Play" feature from 95 is not in NT 4.0, but this is not a feature we will require on this project.

## D.4.7 SELECTION OF DATABASES

### D.4.7.1 Concern for Safety

We have extracted lessons learned from many mishaps including the CFIT accidents in Dubrovnik which claimed Secretary Ron Brown and in Cali, Columbia, site of the American Airlines 767 crash last winter. We are using FAA established frameworks like the new Technical Standard Order TSO-C92C, which address airborne ground proximity warning equipment, so that our warnings will use familiar nomenclature already being promulgated to pilots in all flight regimes.

In terms of Safety Warnings, we have found that FAA Technical Standard Order TSO-C92C, and its associated RTCA DO-161 specifications are the best guidelines we have found and all of their recommended warnings are being integrated. We have used all seven of their warning "modes"

### D.4.7.2 Terrain

Our military version will use the DTED level I data with 3 arc second spacing (roughly 100 meter posting.)

With the help of the NIMA, we have identified a new source of world wide terrain data which will be useful in our Phase III commercialization product to non-military customers. The National Geophysical Data Center has been accumulating terrain data for various parts of the world from a variety of international governments. Their goal is to distribute the consolidated dataset openly in the interest of aviation safety and scientific exploration of the earth's surface. NIMA has recently made a substantial contribution of terrain data to the NDGC collection, and has made their extraction from the NIMA's DTED dataset. DTED, while unclassified, has always been un-releasable outside the military and defense contractor circles. DTED varies in resolution from "Level 1" (with posting every 100 meters) to "Level 5" (with posting every 1 meter). Presently 66% of the earth's surface has been mapped by the DMA level 1 dataset. In order to preserve national security, the data released by NIMA has been subsampled by a factor of 10 in both dimensions (latitude and longitude). The resulting dataset has a posting of 1000 meters. The name for this dataset will probably called DTED "Level 0." The NIMA policy decision makers often quote Secretary Brown's accident in Dubrovnik as the catalyst which is fostering this public release.

We are also following joint discussions between the FAA and the NIMA on release of higher resolution terrain data around the 450 major international airports which are surrounded by dangerous hills. Their current thinking is to have a public release of worldwide 1000 meter resolution data, along with 500 meter resolution data for 50 nm around each airport, and 100 meter resolution data for 10 nm around each airport.

To accommodate this possibility, we explored ways of having the terrain avoidance software integrate different resolutions of terrain data within the same algorithm. JPL is investigating how we could store three different raster resolutions within the same file. We originally favored the use of GEOTIFF 1.0

data format for storing all this raster data, and are encouraged by the notion of adding multiple resolution datasets to our software in this robust and universal, non-proprietary, and commercially accessible format.

During September 1996 NIMA, FAA and the NOS/NOAA signed a memorandum of agreement (MOA) which will contribute a highly important dataset for aviation safety into the public domain. This topic of distributing DMA's terrain data to the public has been discussed in government circles for decades, but it seem the crash of Secretary Ronald Brown's T-43A in the hills near Dubrovnik on March 31 was the reactive catalyst. The first draft of the MOA was penned the following day. Since then we have been in frequent contract with the three principle drivers of this effort: Mr. John Doty at NIMA, Mr. Dick Powell at FAA, and Mr. Ron Bolton at NOAA. We even offered the assistance of our firm in conjunction with our teammates at JPL to help NIMA/FAA/NOAA generate the new dataset, but so far they have only asked us for occasional technical guidance.

Technically speaking, NIMA will allow a thinned subset of their DTED level 1 (100 meter posting) dataset to be distributed in the interests of aviation situational awareness and safety. The FAA has identified the 450 airports world wide where terrain is a significant safety issue for runway approach. The NOS/NOAA aeronautical cartographic group will perform the thinning based on NIMA-specified algorithms, and then sell the data on CD-ROMs to the public. There will be four datasets all based on the NIMA DTED level 1 files:

| Dataset | Resolution | Area |
|---|---|---|
| 1 | 6 arc sec (200 m) | 10 nm around the airports |
| 2 | 15 arc sec (500 m) | 50 nm around the airports |
| 3 | 30 arc sec (1000 m) | world wide |
| 4 | 15 minute (30 km) | world wide |

Note that "world-wide" means everywhere that DTED level 1 data exists, which is only over 66% of the world's terrain. Most of Canada, South America, Australia and Africa are not yet mapped.

The significance of this public release to this project is that it helps to satisfy the "dual use" objective of the STTR funds contracted to us, that is, that the production prototype software be helpful to both military and to the commercial aviation community. We will be designing our system to use the higher resolution DTED level 1 data for military users and to use the medium resolution NOAA dataset for commercial customers.

In conjunction with this NOAA effort, the NIMA is also satisfying the objective of making terrain data available for aviation safety through a second distribution channel. The official opening of the new government bureau known as the National Imagery and Mapping Agency (NIMA) was October 1, 1998. NIMA inherited virtually every DMA employee, as well as those former personnel associated with the National Photographic Interpretation Center (NPIC) and the CIA's Central Imagery Office (CIO). Other resources from the Defense Intelligence Agency, the Defense Airborne Reconnaissance Office Program and the National Reconnaissance Program are also slated.

For the grand opening of the new NIMA World Wide Web Site, Brad Smith of the Air Force DMA support team had the new DTED level 0 dataset posted for download. This has two components. The first is 30 arc second (1000 m posting) data world wide, which is a "thinned" subsample of the current DTED level I (3 arc sec-100 m posting) file. Every 100th point in the high resolution dataset will be sample for this new file. In addition, the second component will be the statistical parameters listing the minimum, maximum and mean values for the 100 points in the original sample. As Dr, Nevin Bryant of the JPL pointed out to the NIMA, these statistical values can serve as seeds for fractal-based imagery which show 3D representations of the terrain. We expect this 2 gigabyte file to be one of the most downloaded scientific datasets every put on the internet. NIMA implemented an impressive server-computer to handle the traffic for this and other previously well guarded data.

Mr. Doty has expressed interest in learning more about our system and the contribution we could make to establish government standards for data formats and protocol. We have already suggested that GEOTIFF 1.0 would be an excellent candidate format for the eventual combination of terrain and obstacle data.

So far the NIMA and FAA are stalled on how to release world-wide obstacle data. (U.S. obstacles to aviation, however, are already distributed to the public by NOAA). The DMA and NOAA are also intrigued by our notions on compression of terrain data for reducing storage requirements in target avionics packages. We will continue to work with these government agencies to our mutual benefit.

We are attempting to accommodate multiple cells of the DTED level 1 (100 meter resolution data) for military use; as well as multiple cells of the newly released NIMA Level 0 (1 km resolution data) for commercial use. On January 15, 1997 Vice President Gore made the official announcement that NIMA was working with the NOS/NOAA, FAA and Department of State to release this dataset to public to enhance aviation safety. Secretary Brown's crash is seen as one of the catalysts for this release. Since then the FAA Situational Awareness for Safety (SAS) Program asked us to make a teleconference presentation to the SAE-G10 committee on aviation safety and charting products. In this presentation, we described to government and industry representatives the details of the new dataset being released by NIMA. Since we already have the complete release on CD-ROM's, we were able to point out characteristics of the dataset which were not obvious in the publicly released press release/announcement. We also suggested that the FAA/SAE-G10 committee adopt the GeoTIFF raster format as the government standard for all these datasets.

### D.4.7.3 Obstacles

Along with map and terrain information, we must also incorporate man-made obstructions into our system. This is one area which we did not try to tackle for our phase I flight tests. Obstruction datasets are important for a variety of reasons. For military pilots flying in a low flying mission, present day forward looking infrared sensors (FLIRs) do a poor job of giving the pilot adequate warning of upcoming towers, smokestacks, and narrow buildings.

First, a FLIR can only see an obstruction out a few kilometers, which equates to only seconds of warning. Second, the detection probability for a modern FLIR, like the Hughes AN/AAQ-16B Hi-Mag, targeted for the SOCOM V-22 Osprey has a detection probability at 2 kilometers for a 3 meter by 3 meter target of only 50%.

Third, the performance is continent on the combination of FLIR wavelength and weather conditions. We understand that while the 8-12 micron varieties of FLIR can see better through dust and sand, its 3-5 micron cousins penetrate high humidity with better clarity. If the pilot is flying in a combination of rain and dust, his FLIR performance is significantly degraded, regardless of wavelength.

There are rarely any specifications on FLIR's for bad visibility environments. So even if the FLIR could depict some of the mountainous terrain to the pilot in time to avoid an accident, it would most likely miss narrow obstacles in bad weather.

Our goal has always been all-weather operation. Obstacle datasets are therefore and important addition to our dataset strategy. Unfortunately, these datasets are far less understood, updated and distributed within the cartographic community than are the terrain datasets. Fortunately, a trio of NIMA liaisons (one from each of the services) has provided us with good insights on the topic and have recently sent us our first prototype obstruction dataset. Special thanks to Brad Smith of the NIMA Air Force support team, LCDR Dave Pashkevich (later continued by Mr. Al Alvarez) of the NIMA Navy Team, and Brian McMullin of the NIMA Army team for their invaluable assistance to our project.

By way of background, the first obstacles were catalogued in the DMA's Digital Feature Analysis Data (DFAD). This dataset has largely dropped from DMA support because of its age and inflexible format. The only consistent users have been the B-2 program who need the reflectivity coefficients off the obstructions as a function of azimuth angle. This allows them to better simulate their radar returns depending on which bearing they are approaching their target. All other obstacle datasets in the military assume isotropic/omnidirectional reflection. For our purposes, isotropic data is best.

The second DMA dataset was the Probabilistic Vertical Obstruction Data (PVOD). These files combine best estimates with actual data and are used for cruise missile planners. The DMA is no longer supporting PVOD and distribution is difficult.

The third set of DMA products is the Vertical Obstruction Data (VOD)/ Digital Vertical Obstruction File. This is the best current collection of worldwide data in the DMA. Unfortunately, distribution requires a manual extraction for the source files for the geographic region of interest. (There are no convenient CD-ROMs like there is for DTED.) The trio of DMA gurus mentioned above, at our request, collaborated in generating an extraction for us from 32-36 north latitude and 116-121 west longitude. This is the area of Southern California where most flight tests were conducted. The region includes about 414 miles by 345

miles, or about 142,000 square miles. In this area the obstacles are listed by descending latitude in an ASCII text file. Our region has 1096 obstacles, for an average of 1 obstruction every 130 square miles.

The fourth NIMA dataset is the new "vector" oriented product called VMAP. In this VMAP family is a member representing aeronautical data called VMAP-AD. Within VMAP-AD will be layers representing the different types of obstacles. The V-MAP AD products have now been cancelled by NIMA, so the DVOF is our main obstruction dataset for the military.

Therefore, we incorporated the DVOF data into our system, due to its present availability and currency. By keeping a good rapport with the NIMA support team, we were able to make several global extractions of this dataset for our development efforts.

### D.4.7.4 JPL/NASA Shuttle Radar Topography Mapper

JPL/NASA in conjunction with the NIMA will launch an interferometric synthetic aperture radar (SAR) on a shuttle mission which will scan the earth's surface over an eleven day period. This project is called the Shuttle Radar Topographic Mission (SRTM) system. The SRTM will generate level II data at 1 arc-second (30 meter) fenceposts that will have an "initial" accuracy of better than $\pm$ 16 meters for one earth pass. The data accuracy is based on the number of shuttle passes over a location on the earth's surface. About four passes are planned. This will put the "intermediate" accuracy of the dataset in the $\pm$ 12 meter range. Then the dataset will be merged with data from another payload on the same shuttle mission called the X-band Synthetic Aperture Radar (XSAR), which has a narrow swath beam. The "final" combined dataset accuracy is expected in the $\pm$ 10 meter range.

JPL has the responsibility for data reduction and verification, as well as for putting the dataset into mosaics of 1 degree latitude by 1 degree longitude. JPL will then turn the data over to DMA who will put the data in the Mil-Standard distribution format for delivery on CD-ROMs. JPL will be developing the software to manipulate the SRTM/XSAR dataset during 1997-8.

The SRTM payload will use a multi-band interferometric synthetic aperture radar (IFSAR) to capture the data. Dubbs and Severino, Inc. is slated as the beta test site for using this IFSAR terrain data extracted from the shuttle mission for our aircraft terrain avoidance system. This data will have two resolutions. The shuttle data which has the same resolution as the existing DTED level I is called Interferometer Terrain Height Data (ITHD) Level I and has the same 3 arc second (100 meter) posting. There is also a ITHD level II data at 1 arc second (30 meter) posting. Two advantages exist for ITHD data over DTED: 1) improved *vertical* accuracy to 16 meters from 50 meters, 2) improved *coverage* to all continents from only 66% of the world.

Because NASA is splitting the $150M costs for the mission with the DOD, they had some say in the releasability of the data. The agreement is that the ITHD level I data will be releasable world wide to the public, while the level II will be reserved for the usual military sponsors. The net effect of this SRTM program on our project is that by designing our software smartly we can accommodate three versions of datasets in one robust architecture across the military and commercial markets:

| Market Segment | Timeframe | Data Source | Resolution |
|---|---|---|---|
| Military | 1997 | DTED I | 3arcsec (100m) |
| Commercial | 1997 | NOAA/DTED 0 | 30arcsec(1000m) |
| Both | 1999 | SRTM ITHD I | 3arcsec (100m) |

This project will therefore satisfy the requirements for "dual use" technology infusion in the marketplace both at the end of the Phase II effort and for future Phase III implementations.

We met with engineers from the Interferometric Radar modeling group who are working on the upcoming Shuttle mission to map the earth's surface with high precision. There is one section of terrain data generated by the Shuttle Endeavor in 1994 which tested the sensor over a long slice of eastern California. We

obtaining this data and run comparisons between its terrain heights and those of the same area from our existing DTED terrain dataset. The correlation was excellent.

### D.4.7.5 Photo Imagery

Since NIMA very few CIB datasets for us, we are creating our own. Our gaming area is most of Southern California and includes over 200,000 square kilometers. See attached map for the boundaries and covered military airbases. For our gaming area we had three levels of detail:

1) LANDSAT Thematic Mapper (TM), resolution 154 meters per pixel, covering entire gaming area
2) USGS National Aerial Photography Program, resolution of better than 5 meters, covering all major airports in the gaming area.
3) Commercial airplane-based photo-imagery, resolution of better than 1 meter, covering only our immediate Irvine area.

We used the LANDSAT TM as the low resolution backdrop. Then we will insert the USGS photo-imagery for the airports. This will be approximately the same resolution that NIMA will be releasing in their CIB database, when they finally buy the data from their commercial sources. The higher resolution Irvine inset allows us to demonstrate the extreme limits of our moving map package with "large scale" databases. Several companies (SPOT Image, Space Imaging, EOSAT, and of course the Soviet distributors) are now selling 1 meter data worldwide and it is only a matter of affordability before every military command has a pool of this high resolution imagery.

### D.4.7.6 Commercial Map Datasets

We partnered with "MAPTECH" to assist in the generation of commercial aeronautical charts. Maptech provided scanned nautical charts on CD-ROM format to boat owners for the last 15 years. They are considered one of the pre-eminent suppliers of digitized nautical map data. This year Maptech has announced a new product line-- digitized aeronautical charts on CD-ROMS. By working with Maptech, we were able to convince them of the wisdom of encoding their aeronautical charts using GEOTIFF (described later) for maximum interoperability between our defense work and their commercial endeavors. They are now scanning the whole series of FAA Visual Flight Rules (VFR) charts currently used by pilots worldwide. Since most pilots are already used to the symbology of the FAA VFR paper charts, a minimum of retraining is required for them to adapt to the electronic moving map display which depict the same colors, text and symbology as their familiar paper charts. GEOTIFF allows these images to be displayed quickly in small image tiles which easily fit in a laptop computer without the need for large amount of RAM. We are exited about this new joint venture and the chance to introduce more open standards to the aviation software industry at large.

### D.4.7.7 Gaming Area

We defined the geospatial parameters of the project's "gaming area." This is the region in which we will conduct ground and flight tests. It is defined cartographically as 32 to 36 north latitude by 116 to 121 west longitude. This area can be thought of as the area which is roughly bounded by the California-Mexico border to the south, Bakersfield to the north, Palm Springs to the east and Lompoc to the west. There is enough geographic terrain diversity in the gaming area to allow testing of all terrain avoidance modes, even with large safety zone parameters. The area also includes over 300 miles of coastal shoreline and the islands of Catalina, San Clemente, San Nicolas, and the Channel Island chain for low level amphibious assault simulation.

For performing both ground tests and flight test for the system, a "gaming area" or "area of interest" has been established. The following NIMA ADRG GNC (1:5,000,000 scale) map illustrates this region.

This area has the following geometric properties:

| Units | Height | Width | Area |
|---|---|---|---|
| degrees | 4 | 5 | 20 |
| nautical miles | 239 | 249 | 59,511 |
| statute miles | 276 | 287 | 79,212 |
| kilometers | 445 | 462 | 205,590 |

From a user perspective it encompasses most of southern California and is approximately bounded by the Mexican Border, Arizona Border, Bakersfield, and the Channel Islands. It includes the following commercial airports of interest: Santa Ana, LAX, Long Beach, San Diego, Palm Springs, Mojave, Catalina. It contains the following military airports which are important to our sponsors: Vandenburg, China Lake, Edwards, Palmdale, San Marcus, George, Norton, March, El Toro, Oceanside, Miramar, Mission Bay, San Nicholas Island and San Clemente Island.

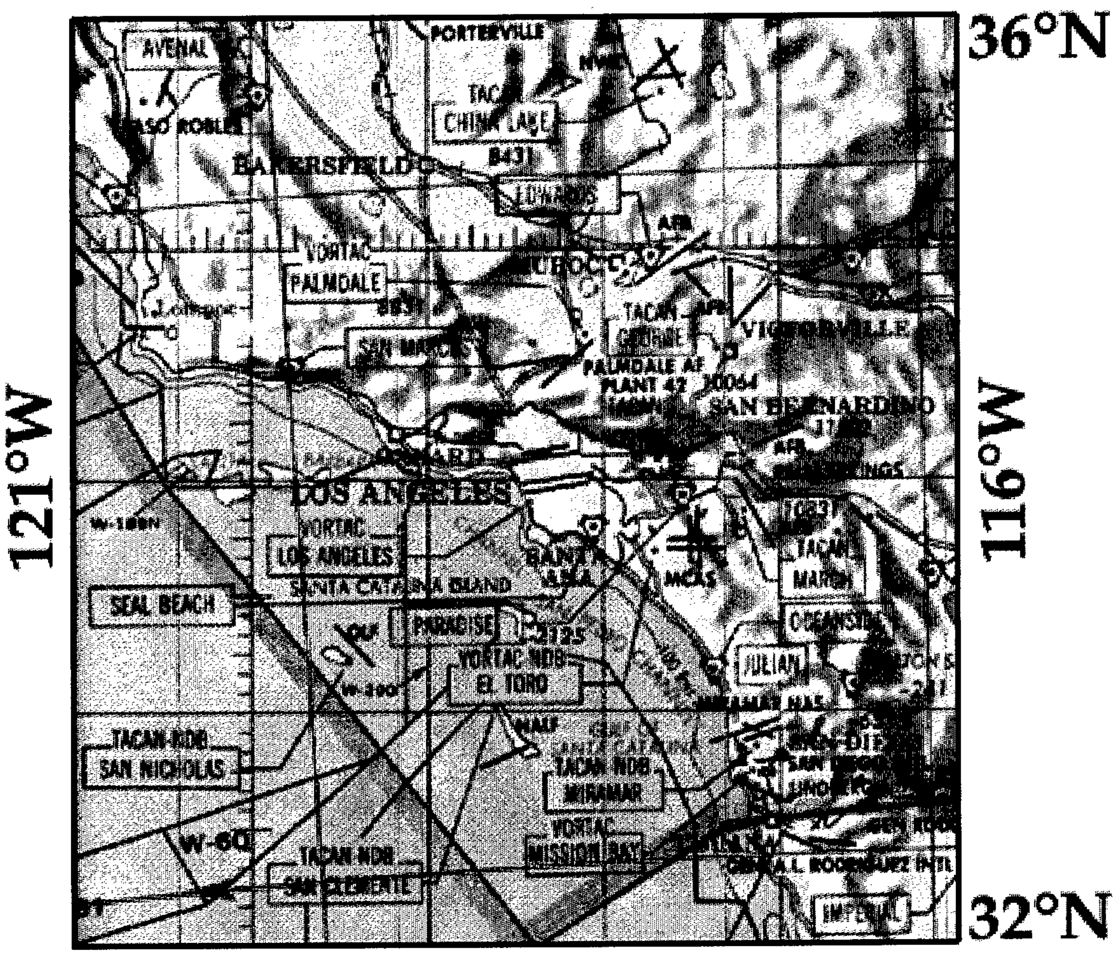



**Figure 4 Southern California Gaming Area for Flight Tests**

## D.4.7.8 Spectrum of Images

The moving map function provides situational awareness to the display by keeping a 2 dimensional image (map, photo, shaded relief) scrolling on the display screen so that the aircraft is always in the center position. In this way the rest the world can be quickly related to aircraft location and flight vector. The following represents a spectrum of the desired charts, maps and images:

a. NIMA/DMA
- GNC (5M)
- JNC (2M)
- ONC (1M)
- TPC (500K)
- JOG-A (250K)
- TLM (50K)
- CIB 10 meter
- CIB 5 meter

b. NOS/NOAA maps digitized by Resolution Mapping Inc.
- WAC
- SAC
- TAC
- IFR Enroute High Altitude
- IFR Enroute Low Altitude

c. JPL
- LANDSAT TM/USGS NAPP+DOQ/I.K.Curtis Photo Mosaic
- Pseudo-Color Shaded Relief images
- Morphed Photo-Imagery

d. NASA/JPL SRTM
- Orthophoto Rectified images
- Land Cover Image

e. USGS
- National Aerial Photography Program (NAPP) 1:40,000 (B+W/Color)
- National High Altitude Program (NHAP) 1:56,000 Color/1:80,000 B+W
- Digital Orthophoto Quad (DOQ)
- Topography maps 1:100,000, 1:250,000, 1:2,000,000

## D.4.7.9 GeoTIFF Graphic Format

### D.4.7.9.1 Introduction

We have had many fruitful dialogues at JPL these past years resolving map data formats. The format called "GEOTIFF 1.0" was our foundation map and photoimagery data protocol. A brief history is warranted here. TIFF or Tagged Image File Format is a digital schema for storing raster graphic data which was developed by the Aldus Corporation and is in the public domain. The latest version 6.0 includes the

cartographic tag extensions developed by the Jet Propulsion Laboratory, which allow the storage and retrieval of cartographic data (lat and long) from within the image file itself. GEOTIFF is a group of industry-standard tag sets for the management of georeference or geocoded raster imagery using this TIFF foundation standard. (GEOTIFF is an extension of TIFF) Written and pioneered by Dr. Niles Ritter at JPL, The GEOTIFF 1.0 specification defines a set of TIFF tags provided to describe all cartographic information associated with TIFF imagery that originates from satellite imaging systems, scanned aerial photography, scanned maps, digital elevation models, or as a result of geographic analysis. Its aim is to allow means for tying a raster image to a known model space or map projection, and for describing those projections.

The net effect of our project baselining all 2D map datasets using GEOTIFF is that it allows our software moving map module to have the maximum portability to other TIFF applications, and to display the large amount of georeferenced TIFF data already available, or planned for the future. For example, the Shuttle Radar Topographic Mapper mission has now been funded by DOD, and NASA has established a mission date of September 15-26, 1999. JPL will be processing all the SRTM data in GEOTIFF format for maximum promulgation to the defense, research and scientific communities. We believe our adoption of this important open, non-proprietary format helps boost our terrain avoidance software into more application markets, like those who need the IFSAR datasets for their projects.

To introduce the main topics, the following technical sections will cover the POSC Geodetic Model and of the GeoTIFF standard. Dubbs & Severino, Inc. is working with the Jet Propulsion Laboratory in Pasadena, CA to promote both as baseline standards for geographic research.

## D.4.7.9.2 The EPSG/POSC Geodetic Model

All geographically mapped information which is processed by quality software must reference the same geodetic model. A geodetic model is a reference system which quantitatively specifies the mapping of all points on the surface of the earth to a three dimensional coordinate system. Such models include the family of coordinates and transformations which map from one reference system to another. A geodetic model is composed of four components: 1) a geocentric model, 2) a geographic datum, 3) a projected coordinate system, and 4) the algorithms which specify implementation of the projected coordinate system.

1) The *geocentric model* is an earth-centered, earth-fixed representation that defines the position of a point with respect to the center of the earth. An example of a well recognized geocentric model is the "WGS-84 Geocentric Model" which defines points in terms of a Cartesian coordinate system (X,Y,Z).

2) The *geographic datum* is the equivalence relationship between the Cartesian coordinate system and the geodetic coordinates (also called geodetic positions) which is expressed in terms of latitude, longitude and geodetic height and defines the position of an earth-surface point with respect to a reference ellipsoid. An ellipsoid is a surface generated by rotating an ellipse about one of its axes. An example of a well recognized geographic datum is the "WGS-84 Ellipsoid Model."

3) A *projected coordinate system* , also called a map projection, is the function relating the coordinates of points on a curved surface (like an ellipsoid) to coordinates of points on a plane. The most precise map projections are established by analytical computation (as opposed to geometric construction). An example of a well recognized projected coordinate system is the "Transverse Mercator Map Projection."

4) The *algorithms* defining a specified project coordinate system are the algebraic formulas and their associated projection parameters and scale factors which numerically minimize the distortion always introduced by map projection.

Together these four components of the complete geodetic model allow accurate mapping of points on the earth to points on a map representation or geographic dataset.

Over time, earth scientists have introduced many geodetic models, both local and global in scale. The European Petroleum Survey Group (EPSG) in conjunction with the Petroleum Open Software Corporation (POSC) has codified all recognized components of these geodetic models into a single coherent metadata standard. Because petroleum scientists had to consider all the various technical and political factors of worldwide drilling, and be able to correlate the coordinates found in local datums to global references, and also accommodate historically derived coordinates using antiquated datums, they became the de-facto group to codify all geodetic models. Their complete work is now accepted by earth scientists on all continents and is implemented in Microsoft Excel spreadsheets found at our ftp site (described later).

One advantage of using the EPSG/POSC Tables is that all four components of the Geodetic Model are referenced by simple index numbers which can be interpreted by the GeoTIFF raster format (see next section).

For example, if we wanted to design a geographic dataset for Washington D.C., we could specify the following EPSG/POSC index numbers:

**Index Specification**

| Geodetic Model Component | Selection | Area of Use | EPSG/POSC Index |
|---|---|---|---|
| Geographic Coordinate System including Geodetic Datum | WGS-84 | World | 4326 |
| Projected Coordinate System including algorithms | UTM zone 18N | North Hemisphere 72-78 degrees West | 16018 |

**OR**

**Complete Model Specification**

| Geodetic Model Component | Selection | Area of Use | EPSG/POSC Index |
|---|---|---|---|
| Complete Geodetic Model | WGS-84/ UTM zone 18N | North Hemisphere 72-78 degrees West | 32618 |

**Figure 5 GeoTIFF EPSG/POSC Index Numbers Example**

If we consistently apply the same transformation methods and algorithms, the EPSG/POSC tables and indexes provide global horizontal accuracy to 1 centimeter.

There are three benefits derived from geographic software development using the EPSG/POSC Geodetic Model:

1) All the scientific principles of complex geodetic models are reduced to the use of simple index numbers.

2) World wide deployment of aviation equipment and products is facilitated through support for both local and global geographic datums and map systems.

3) The implementation details within a geographic region are made transparent to the end-user by simply specifying the index number (like "32618" in the above example) in your GeoTIFF dataset.

## D.4.7.9.3 The GeoTIFF Raster Format

We highly recommend that the GeoTIFF Version 1.0 format be used for all geographically oriented datasets. GeoTIFF is rapidly becoming the de-facto standard for geographic raster datasets in companies and government agencies around the globe. It is used by 250 subscribers in 100 countries. The U.S. Geological Survey (USGS), the National Aeronautics and Space Administration (NASA), the National Imagery and Mapping Agency (NIMA), the United Kingdom Military Survey, SPOT Corp., and Space Imaging Corp. are all adopting GeoTIFF as one of their geographic raster data interchange formats. It is non-proprietary, license-free and integrates easily with the EPSG/POSC Geodetic Model tables (see above section).

A variety of companies currently or will soon provide GeoTIFF compatible software. These suppliers include: Intergraph, ESRI, Applied Global Technologies, ERDAS, PCI, ER Mapper, Softdesk, DataDoors, Laser-Scan, Innovative Vision, Python Imaging Library, Able Software, MapInfo, MicroImages and BBN. (See attached list in Appendix A.) A variety of compression/decompression formats are part of the parent TIFF specification including both lossless and lossy forms: PackBits, Modified Huffman Compression, CCITT Bilevel, LZW, and JPEG.

The GeoTIFF standard can support our community's research in several important ways:

1) It provides an open, de-facto standard which all contributors can use to exchange data.

2) It integrates the EPSG/POSC Geodetic Model Tables in a manner which accommodates all recognized datums, both global and local, and all common map projections. It accomplishes this though the use of simple index numbers. This approach provides an underlying accuracy of 1 centimeter anywhere on earth.

3) It allows large files to be "tiled" in a series of adjacent pieces of a mosaic. Only those tiles which are currently being read, displayed or manipulated need access to the computer's RAM memory--the rest remain on disk. This allocation scheme minimizes the hardware requirements of the processing computer, while still supporting access to complex and multi-level datasets. For example, we have demonstrated the ability to access individual tiles quickly within a 1 Gigabyte+ dataset on a standard, inexpensive laptop computer.

4) It allows manipulation of 3D datasets with precise elevation postings. As our product line makes advances in its 3D capability, the research community can leverage the advantages of correlating terrain with maps, photo-imagery, pseudo-color shaded reliefs and our "morphed" imagery maps.

5) It facilitates integration of existing vector data such as ARCINFO GIS files or other vector files.

6) It lets multiple images/datasets be stored in the same file. A hierarchy of interlocking raster matrices can be manipulated in a coherent and aligned GeoTIFF file, even if the underlying datasets overlap, cover different regions, or are of different resolutions and posting accuracies.

The GeoTIFF format is a subset of the Tagged Image File Format (TIFF) raster data interchange. The TIFF format is the one of the most popular raster data formats used around the globe. The specification for the current version, TIFF Revision 6.0 is provided as Appendix B. TIFF was developed by Aldus and Microsoft Corp, and the specification was owned by Aldus, which in turn has now merged with Adobe Systems, Inc. They maintain the specification and distribute documentation on it freely and without license. TIFF is intrinsically non-proprietary. Management of the TIFF specification by Aldus allows them to maintain the "tags" which denote attributes about the raster images in very precise and standardized ways. This allows for compatibility among all users.

Our teammates at the Jet Propulsion Laboratory/Cartographic Application Group (JPL/CAG) helped develop a tag set for the TIFF specification which allows geo-referencing of map images. A GeoTIFF file is simply a TIFF file which uses these geo-referencing and geo-coding tags. A GeoTIFF file is a TIFF version 6.0 file and inherits the file structure as described in the TIFF specification. The GeoTIFF Format Specification Version 1.0 is included as Appendix C.

JPL maintains the parameter values essential to the GeoTIFF tags and assigns these values in support of the global geographic community. They have designed the tags to reference the EPSG/POSC index numbers described in the previous section of this letter. In addition to incorporating any of the standard geographic coordinate systems, geocentric coordinate systems, and projected coordinate systems, the tags also allow developers to specify a custom system. When a commercially available software browser/reader opens a GeoTIFF file, it expands the tag and automatically adjusts the image to correspond with the referenced coordinate system.

Our teammate, Dr. Niles Ritter of JPL/CAG developed the GeoTIFF standard and the GeoTIFF Web site. Since then the JPL transferred the GeoTIFF web site to the USGS because it would recevied wider visibility there. The current site is http://mcmcweb.er.usgs.gov/drg/geotiff.html.

In late 1998 the Office of the Secretary of Defense contracted with Dubbs & Severino, Inc. and with JPL to develop the next generation GeoTIFF architecture. Called GeoTIFF version 2.0 this technology will chiefly allow the incorporation of multi-scale nested datasets to exist in the same file. In addition, 64 bit addressing will allow files greater than 4GB to be accessed, and a greater variety of lossless compression options will be offered. Future advancements to this architecture will be posted to many sites on the Internet, including our own www.position-integrity.com.

## D.4.8 SOFTWARE REQUIREMENTS

### D.4.8.1 External Interface Requirements

#### D.4.8.1.1 GPS Navigation Data.

Accurate time, 3D position, and navigational data were provided through HOL function calls to access GPS data in real time.

##### D.4.8.1.1.1 HOL Function calls

HOL Function calls were provided which:

a. Get Longitude degrees (integer, east longs are positive, west longs are negative)
b. Get Longitude minutes (double precision decimal, to 1/10,000 minute)
c. Get Latitude degrees (integer, north latitudes are positive, south latitudes are negative)
d. Get Latitude minutes (double precision decimal, to 1/10,000 minute)
e. Get Altitude (double precision, always positive, height above Mean Sea Level)
f. Get Heading (double precision, magnetic azimuth, course over ground, to 1/10 degree)
g. Get Track (double precision, magnetic azimuth, aircraft pointing angle, to 1/10 degree)

h. Get velocity (double precision, horizontal speed vector, feet per minute)
i. Get vertical speed (double precision, vertical speed scalar, feet per minute, up is positive, down is negative.)
j. Get Slant range (double precision, elevation angle from horizon, up is positive, down is negative.)
k. Get time (UTC format)
l. Get GPS receiver status (time only, 2D position, 3D position, DGPS, SGPS)

### D.4.8.1.1.2 NMEA 0183 V2.1 (Nov 94) Sentences

a. Use GLL or RMC sentence for latitude, longitude, time of fix. Coordinates are output in dddmm.mmm, with a resolution of a thousand of a minute. At the equator this yields a horizontal resolution of about 6.1 feet. The horizontal accuracy using P (Y) code with WAGE is about 4 meters.

b. Use GGA sentence for altitude. Height is MSL and is output x.x meters with a resolution of 0.1 meters. This yields a vertical resolution of about 4 inches. The horizontal accuracy using P(Y) code with WAGE is about 6 meters. To the MSL altitude must be subtracted the Geoidal Separation (also output in this sentence.) The Geoidal Separation is defined as the difference between the WGS-94 earth ellipsoid and mean sea level. If mean sea level is below the ellipsoid, the Geoidal separation is negative. Both altitudes are used and must be output. Use the MSL altitude to compare with the DTED value for terrain avoidance; use the WGS-84 altitude for display to the pilot. Also get the GPS quality (no fix/SPS fix/DGPS fix/PPS fix) and the number of satellites being tracked for the pilot status display. For commercial navigation using DGPS, also get the time since the last RTCM-104 message update from the DGPS receiver.

c. Use the GSA sentence to get the PDOP, HDOP and VDOP values for the pilot's status display.

d. Use the VTG sentence to get ground track in degree magnetic (never display the track in degrees true to the pilot). Also get the speed in knots (not kilometer per hour). Resolution is a tenth of a degree and a tenth of knot.

### D.4.8.1.2 Terrain Data

Terrain data will be used to compare the aircraft's flight vector with the earth to determine if CFIT impact is possible. One of three different datasets is used, depending on the customer. The military dataset is used by the Army, Navy and all other authorized government programs. The commercial dataset will be used by the Seagull GAIMS, Avidyne Flight Computer and for distribution to general aviation customers. The advanced/scientific dataset is used to prepare for the upcoming Shuttle mission and will be the military/commercial standard database in 1999.

All data will be reformatted from its native format into GeoTIFF 1.0 by JPL.

### D.4.8.1.2.1 Military Dataset

DTED level I data with 3 arc second (3") or 100 meter posting will be used worldwide.

### D.4.8.1.2.2 Commercial Dataset

NIMA's new DTED level 0 data with 30" or 1000-meter posting will be used worldwide. This data has four files. One file has a single north west point from the matrix of the underlying 100 original DTED level 1 (3") points. The second file has the minimum, maximum and maximum for the 100 original points from DTED level 1. For our system, the maximum points will be used.

Two additional levels of detail will augment this low-resolution data. The government has established a list of about 450 "terrain impacted airports" worldwide. For each of these airports tow circular patches of data will be provided. For a radius of 50 nautical miles around each airport, 15" or 500 meter posting data will be provided. For a radius of 6 nautical miles around each airport, 6" or 200 meter posting data will also be provided. NOAA will prepare these two datasets to use maximum values from the underlying DTED level 1 data.

### D.4.8.1.2.3 Advanced Dataset

When the SRTM mission flys in 1999, JPL will provide level 1 and level 2 (1" or 30 meter posting) data worldwide. Our system must be designed to accommodate this higher resolution dataset. We have JPL data from a 1994 Endeavor flyover of California using the SIR-C IFSAR radar (an imaging radar similar to the one to be used in 1999). This data has posting at 30 meters. The flight path generated a dataset about 400 miles long by 30 miles wide. We need to demonstrate our system using this preliminary dataset.

### D.4.8.1.3 Obstacle Data

Obstacles are man made objects like high voltage electric towers, radio beacon antennas and tall buildings. Database entries for power lines (the wire running between electric towers) information is sufficiently sparse that it will not be considered. Obstacle data must be logically "ored" with terrain data to yield the composite topology that the aircraft must avoid. Obstacle data is listed in point files with each record listing the latitude, longitude, height, quality, and datum for the obstruction.

### D.4.8.1.3.1 Military Version

The worldwide NIMA Digital Vertical Obstruction File (DVOF) will be used. For those entries with a Quality level of 1 and using WGS-84 datum, only a point obstruction need be inserted into the terrain. For data with quality levels of 2-7 or for data using other than WGS-84 datums, a region of least 6" x 6" (200 meters by meters) will be designated. This process is sometimes called forming "umbrella" regions, since the probability of the obstacles presence falls off slowly around its stated horizontal position. Height is given per MSL and AGL. The DVOF includes quality- validated WGS-84 obstructions points, primarily collected around airports.

### D.4.8.1.3.2 Commercial Version

The U.S. NOS/NOAA DOF will be used. It tracks obstacles only higher than 500 feet, but most points have been validated and so no umbrella region need be created. Height is given AGL.

### D.4.8.1.3.3 Advanced Version

The SRTM IOD will be used. The format for this data is in process, but all data will have a high quality and referenced to the WGS-84 datum.

### D.4.8.1.4 2D Image Data

2 dimensional / map data will be presented via the Moving Map Function. This function will run in a preemptive multitasking basis with the terrain avoidance function. All map data will be in GeoTIFF 1.0 using tiled dynamic data retrieval from a separate disk (HDD, CD-ROM, Magneto-Optical or DVD). Map data to be presented include:

a. NIMA/DMA
    GNC (1:5M)
    JNC (1:2M)
    ONC (1:1M)
    TPC (1:500K)
    JOG-A (1:250K)
    TLM (1:50K)
    City Graphics (various from 1:20K to 1:7K)
    CIB 10 meter
    CIB 5 meter

b. NOS/NOAA maps digitized by Resolution Mapping Inc.
    WAC (1:1M)
    SAC (1:500K)
    TAC (1:250K)
    IFR Enroute High Altitude
    IFR Enroute Low Altitude

c. JPL

LANDSAT TM/USGS NAPP+DOQ/I.K.Curtis Photo Mosaic
Pseudo-Color Shaded Relief images
Morphed Photo-Imagery
Digital Earth LANDSAT Mosaic

d. NASA/JPL SRTM
Orthophoto Rectified images
Land Cover Image

e. USGS
National Aerial Photography Program (NAPP) 1:40,000 (B+W/Color)
National High Altitude Program (NHAP) 1:56,000 Color
1:80,000 B+W
Digital Orthophoto Quad (DOQ)

Topography maps 1:100,000, 1:250,000, 1:2,000,000

### D.4.8.1.5 Airport Runway Data

This data will assist the pilot in determining the location of the nearest airport, the runway orientation and geometry, tower frequencies, and other data.

#### D.4.8.1.5.1 Military Version

The NIMA DAFIF Edition 6 files will be used to present both text and graphical data when selected. The airport family of records (file 0, formats 1-19) will be used. These data are updated every 28 days.

#### D.4.8.1.5.2 Commercial Version

DAFIF is being distributed in the public domain. If releasable to the public, this dataset should be used for all market segments. If not releasable the following datasets should be used:

- The FAA/Aeronautical Information Services/ATA-100 Landing Facility Data Base Record "APT" file will be used for facilities in the U.S. These data are updated every 28 days.

- The International Civil Aeronautical Organization (ICAO) ACDB file will be used for major facilities worldwide. These data are updated every 365 days.

### D.4.8.2 Software Capability Requirements

#### D.4.8.2.1 Navigational Setups

Three navigational setups will facilitate testing and integration. Only one setup is required at a time.

### D.4.8.2.1.1. Laboratory Simulation Setup

In this setup, all navigational inputs will be simulated. A text file will be processed which contains an unlimited number of waypoints. Each waypoints will contain a latitude, longitude, altitude, heading, slant angle, and speed. The user is allowed to single step the system through the simulation either one waypoint at a time or at a fixed rate of 1 waypoint per second.

### D.4.8.2.1.2 Ground Test Setup

In this setup, the latitude, longitude, heading and speed are input from the GPS receiver. The user as allowed to input altitude and slant angle. The system will use the altitude and slant angle values until the operator changes them.

### D.4.8.2.1.3 Flight Test Setup

In this setup, all navigation inputs are read from the GPS receiver.

### D.4.8.2.2 Operating modes

There are six operating modes for terrain avoidance. Five of these modes comply with the conditions for alerting pilots as found in FAA TSO-C92c (Airborne Ground Proximity Warning Equipment) and RTCA DO-161A (Minimum Performance Standards-Airborne Ground Proximity Warning Equipment). The approach that ARAD will take is to replace reliance on the older Instrument Landing System (ILS) and radar altimeter analog devices referenced in these documents with modern GPS digital technology. There is an additional mode for altitude callouts. Any mode that references "terrain" includes both natural topographic relief as well as man-made obstacles and obstructions.

### D.4.8.2.2.1 Mode 1 - Excessive Rate of Descent with Respect to Terrain

If the aircraft is less than 2500 feet AGL, and the sink rate is greater than 1000 feet per minute, and the ratio of the change in forward looking AGL altitude to the change in sink rate is less than 0.71 then generate a "sinkrate" warning. This is an audio warning which sounds: "Whoop-Whoop" followed by "Sinkrate, Sinkrate". The "Whoop-Whoop" is described as a tone sweep from 400 Hz to 800 Hz at a period of 0.3 seconds. Repeat as long as situation exists, unless a more severe warning condition is present.

In the above case, if the ratio is becomes less than 0.38 then substitute "Pull Up, Pull Up" for the Sinkrate warning.

### D.4.8.2.2.2 Mode 2 - Excessive Closure Rate to Terrain

If the aircraft is between 1000 and 2000 feet AGL, and the terrain closure rate is greater than 2000 feet per minute, and the ratio of the change in forward looking AGL to the change in closure rate is less than .75 then generate a "terrain" warning. This is an audio warning that sounds: "Whoop-Whoop" followed by "Terrain, Terrain".

If the aircraft is between 0 and 1000 feet AGL, then substitute "Pull Up" for the "terrain" warning.

### D.4.8.2.2.3 Mode 3A - Negative Climb Rate Before Acquiring 700 Feet Terrain Clearance After Take-Off

If the aircraft is less than 700 feet AGL and the ratio of change in AGL altitude to change in sink rate is less than 1.4 then generate a "Don't Sink" warning. This is an audio warning that sounds: "Whoop-Whoop" followed by "Don't Sink".

### D.4.8.2.2.4 Mode 3B - Altitude Loss Before Acquiring 700 Feet Terrain Clearance After Take-Off

If the aircraft is less than 700 feet AGL and the ratio of change in AGL altitude to change in accumulated altitude loss is less than 10.0 then generate a "Don't Sink" warning.

### D.4.8.2.2.5 Mode 4 - Flight Into Terrain With Less Than 500 feet Terrain Clearance

If the current flight vector projects that the aircraft will be less than 500 feet AGL, then generate a "Too Low, Terrain" warning. This is an audio warning that sounds: "Whoop-Whoop" followed by "Too Low, Terrain". If the pilot is on a 3% glideslope towards landing at (or just taking off from) a runway listed in the DAFIF runway database, then no warning is generated. If the user selects a "Clearance Safety Margin" in the user setup menu greater than 500 feet, then provide this Mode 4 warning for that threshold. If the user selects a margin less than 500 feet, and this threshold is exceeded, then generate a "Caution-Hugging Terrain" warning without the "Whoop-Whoop" This is for nap of the earth flight by the military special forces.

### D.4 8.2.2.6 Mode 5 - Excessive Downward Deviation From 3% Glideslope

If the aircraft is less than 1000 feet AGL an is on approach to one of the runways listed in the DAFIF database, and the glideslope falls outside the range entered in the user set up window (usually centered around 3%), then generate a "Glideslope" warning. This is an audio warning that sounds "Glideslope". (No Whoop-Whoop is used.)

### D.4.8.2.2.7 Mode 6 Altitude Callouts

When the aircraft is on 3% glideslope approach to a runway listed in the DAFIF database, then generate an altitude callout at the following AGL points: "1000 feet", "500 feet", "200 feet" and "50 feet". This feature can be deselected through the user set up menu.

### D.4.8.2.3 Moving Map Function

The moving map function provides situational awareness to the display by keeping a 2 dimensional image (map, photo, shaded relief) scrolling on the display screen so that the aircraft is always in the center position. In this way the rest the world can be quickly related to aircraft location and flight vector. For map data, a north-up orientation is maintained so that the rasterized text is always easily readable. For photo-imagery and shaded relief images, either north up or track formats are acceptable. The source of the data to be displayed is listed in section 3.1.4. All image data will be in GeoTIFF 1.0 format with its associated 1)integral georeference tags, 2)tiled mosaic display, 3)dynamic data retrieval from disk, 4)ortho rectification and 5)one of the compression techniques per the TIFF 6.0 specification. The following features in the moving map function are required:

a. 4 simultaneous images, including different files or multiple resolutions of several files.
b. 2nd order georeferencing to warp polyconic projection datasets in standard TIFF 6.0 format.
c. zoom in/out
d. distance on map/"rubber band" function with readout in nautical miles
e. route/waypoint planning capability
f. track history/"bread crumb" function with UTC time tagging
g. 0.1 to 10x speed display playback function
h. selectable text display of current lat, long, alt, speed, heading, slant angle, local time
i. user addition of lines, boxes, circles on images (without writing permanently to image file)
j. "within radius" alarm of designated waypoint
k. growth for displaying other dynamically updated track data in correct geo-referenced position.

### D.4.8.3 Software Internal Interfaces

The application will be able to access DTED data on local hard disk or CD-ROM. GPS access will be either on a local serial port, or via TCP-IP protocol to another computer on the same network.

### D.4.8.4 Software Data Element Requirements

The application will keep with RAM the DTED cell being overflown, as well as the eight adjacent 1 degree by 1 degree cells. As an adjacent cell is entered, the application will immediately fetch the next adjacent DTED cell, while simultaneously releasing the cell two adjacent blocks behind it. In this way the steady state RAM requirements will be for nine DTED cells or roughly 27MB.

### D.4.8.5 Software Adaption Requirements

The application will process GPS position and navigation data and present graphic, textual and audio alerts if any warning mode criteria are violated.

### D.4.8.6 Operational Parameters

The application will use Microsoft Foundation Class library routines to give the Windows Application "Look and Feel" This includes the ability to move, "iconify", and delete the window presented. In addition Windows calling protocols will be used for program execution and priority interleaving with other applications running on the same computer.

### D.4.8.7 Sizing and Timing Requirements

The program application, minus DTED data will fit on a floppy disk, thereby consuming less than 1.4 MB of hard disk space. The steady state amount of RAM required will be less than 30MB, including the nine DTED cells. The application will cycle through the 60nm x 60 nm of terrain data around the aircraft and perform this loop every four seconds.

### D.4.8.8 Safety Requirements

The application should be started and tested before take-off to insure that all modules are active and processing correctly. The mode display should indicate if the GPS unit is providing updates of position and navigational information.

### D.4.8.9 Security Requirements

To prevent unauthorized copies of our software from being distributed the Rainbow Sentinel hardware device will be installed on the computer's parallel port and integrated into the system.

Under DFARS clause 252.245-7000 all Mapping Charting and Geodesy data from NIMA is considered government furnished data and shall not be duplicated, copied or otherwise reproduced and distributed outside this firm and its direct subcontractors.

### D.4.8.10 Design Constraints

The application shall be designed to run under the Microsoft Windows NT operating system will service pack 4 installed. Because of the premptive multi-tasking capability required to alternate between GPS data fetch and ARAD module processing, the Windows 95 and 98 operating system cannot be used.

### D.4.8.11 Software Quality Factors

The system will be documented using Microsoft Foundation Class quality standards as described in the Microsoft Certified Solution Provider courses and training material.

### D.4.8.12 Human Performance/Human Engineering Requirements

The system user interface will be trial tested before a staff of qualified pilots in order to pass a minimum usability threshold. Comments will be incorporated into the user interface before final delivery.

### D.4.8.13 Software Qualification Requirements

### D.4.8.13.1 Qualification Methods

The system will be flight tested four times. One of these flight tests will be on a rotary wing aircraft. Of the four flight tests, at least two will be performed back to back, within 90 minutes of each other, for repeatability testing. The 90-minute threshhold is to insure a comparable GPS satellite complement for both flight tests.

### D.4.8.13.2 Special Qualification Requirements

The GPS receivers will be keyed for P(Y) code use, so that positional accuracy will be better than 12 meters horizontal and 16 meters vertically.

## D.4.9 OPERATING INSTRUCTIONS

### D.4.9.1 Operating Instruction Overview

The GPS-Based Terrain Avoidance System, also known as "TerrAvoid" is a Windows NT application written to help pilots fly more safely in the vacinity of mountainous terrain, especially at night or in bad weather. Because pilots have enough to do flying their aircraft, the system was designed to be fully automatic, and require no user interaction during flight to be fully effective. While the system has a

graphic display, the pilot does not even have to view that to keep the aircraft from straying into dangerous situations. This is due to our unique audible warning alerts, which will allow the system to give the pilot many minutes of warning time before an CFIT accident is immanent. After receiving a audible alert, then the pilot may choose to view his/her situation awareness on our intuitive graphic display to assess the proper exit strategy out of the dangerous flight vector. For these reasons, the system has been regarded by test pilots as simple, effective and essential to flight where 100% VFR conditions cannot be fully maintained.

## D.4.9.2 Core Programs

Several programs or Windows applications make up the GPS-Based Terrain Avoidance System. They are 1) GPS Monitor, 2) FlightSim Monitor, 3) TerrAvoid, and 4) Position Integrity Tactical Display. The GPS Monitor program is a hardware interface with the navigation data being input into the computer's serial port from a GPS receiver. The Flight Sim Monitor performs a similar function with Microsoft Flight Simulator 98 program, and allows simulation of GPS navigation using the FS98 flight stick controls. TerrAvoid and Position Integrity Tactical Display use the navigation information from either the real GPS or the simulated navigation datastreams and generate the appropriate situation awareness screens and warning queues.

### D.4.9.2.1 GPS Monitor

The GPS Monitor Program is a low-level application which works with the Windows operating system to route GPS messages from the computer serial port into the navigation software application. GPSMON can access positional, navigation and satellite updates from a single GPS receiver and output this information to multiple applications which need it. In addition GPSMON could also access data streams from multiple GPS units (up to 128 of them) and network these updates to all applications running on the same computer. In this way, future functionality is provided now so that new applications like the JTIDS link can be integrated seamlessly.

Select START, SETTING, CONTROL PANEL, and double click on GPS Receivers. The GPS Control Panel will open.

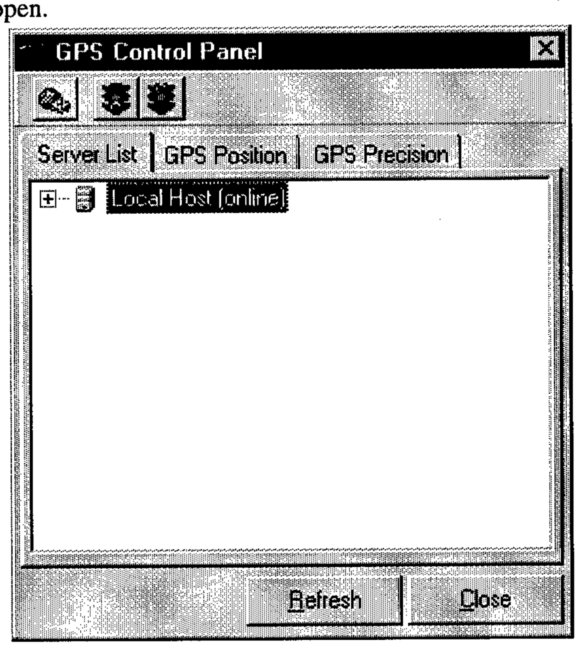



**Figure 6 GPS Control Panel Dialog Box**

Click on the Green Signal Icon. This will bring up the Start GPS Dialog Box.

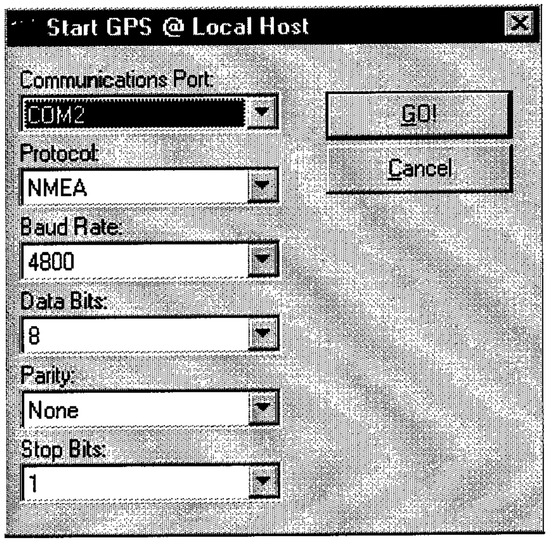



**Figure 7 Start GPS Dialog Box**

After confirming that all the Communications Port Settings are correct, press GO! This will start the receiving of NMEA sentences from the GPS receiver into the computer. In the main box of GPS Control Panel, press the Plus sign to start the GPS Monitor Scan of all available GPS receivers hooked up to the computer. When this process is finished the COM1:4800:8:N:1 will appear next to an icon of a satellite.

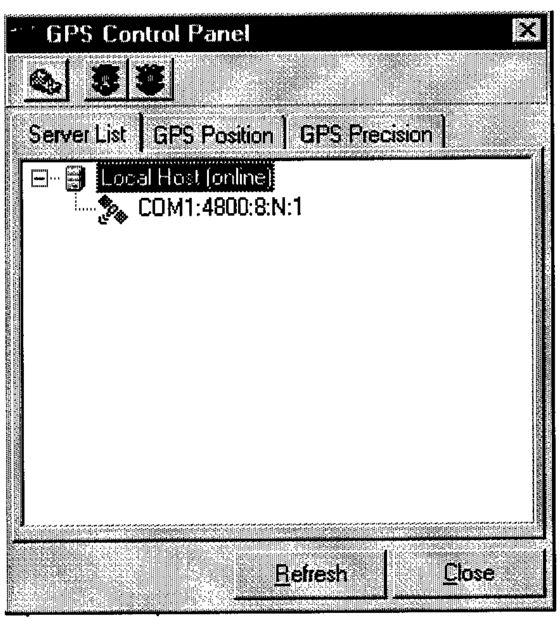



**Figure 8 GPS Control Panel Display**

Select the Satellite Icon with the COM1 information and select the GPS Position tab. The following GPS Position information box will appear:

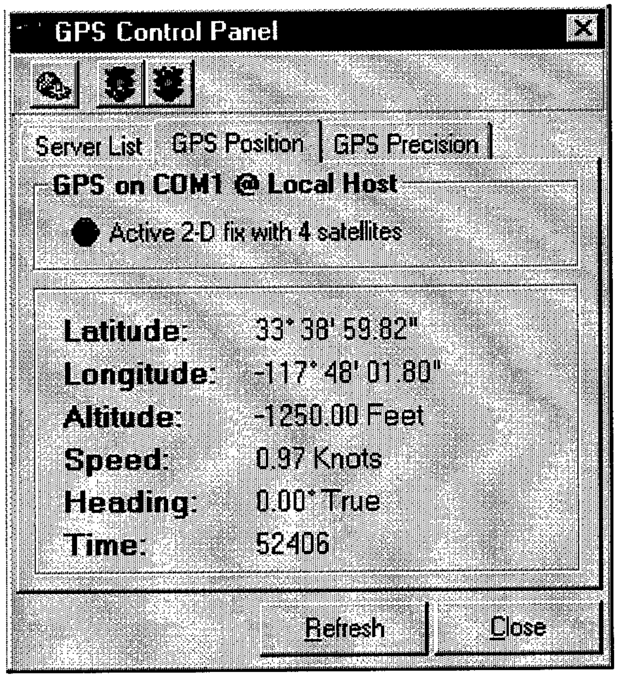



**Figure 9 GPS Contol Panel-GPS Position Display**

This screen shows all the necessary information about position, velocity and satellite status. Next select the GPS Precision tab. The following information display will appear:

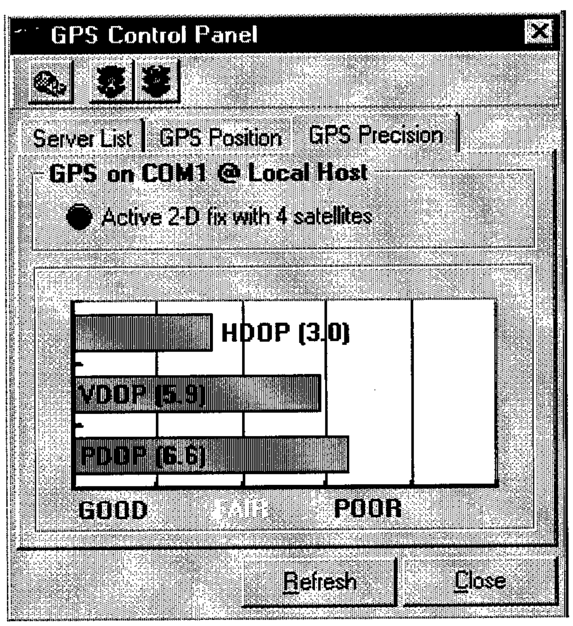



**Figure 10 GPS Control Panel-GPS Precision Display**

This screen shows the various Dilution of Precision metrics about the GPS active fix. Once the GPS Position and Precision have been inspected for being acceptable, the GPS Monitors windows can be exited. (The program is still running in Windows NT background mode.)

### D.4.9.2.2 FIGHT SIM Monitor

During our Phase I development, we developed a minimal capability to test the Terrain Avoidance System through a waypoint simulator. While this was an excellent tool for static point testing, our Phase II effort required a more dynamic simulator capability. Rather than developing one from scratch, we instead use the Microsoft Flight Simulator 98 (FS98) software program (available for about $50) which is shown below, and we developed a custom interface which allows the simulated aircraft' position and velocity to be translated into WGS-84 navigation data. In this way wherever the simulated aircraft flys in FS98, TerrAvoid will behave as if it were a Terrain Avoidance display in that cockpit. FS98 is extremely flexible tool for testing since it has a "slew" mode which will move the aircraft in any direction and speed, including standing still in space. Because we are Microsoft Solution Providers, we have access to internal Microsoft documentation that allowed us to develop this custom interface to FS98.

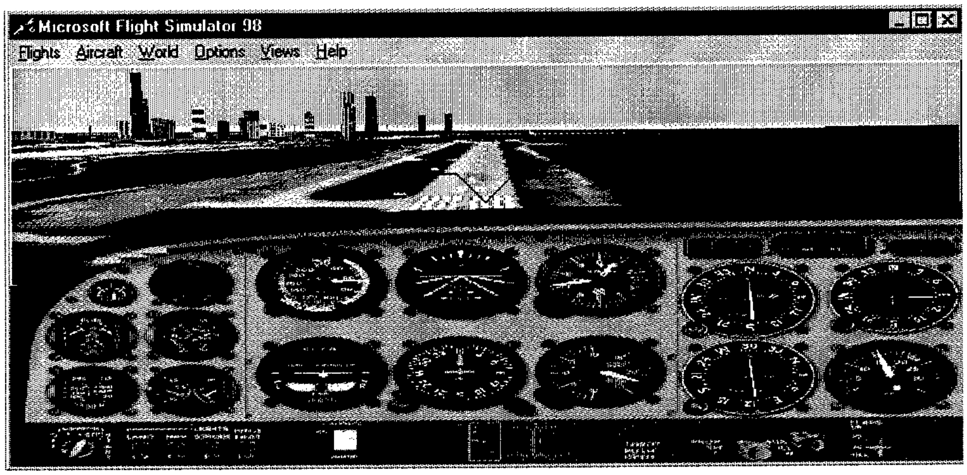



**Figure 11 Microsoft Flight Simulator Display**

After starting FS98, and loading the flight desired, select Start, Programs, MS Flight Simulator Monitor, Flight Simulator Monitor. The following screen will appear:

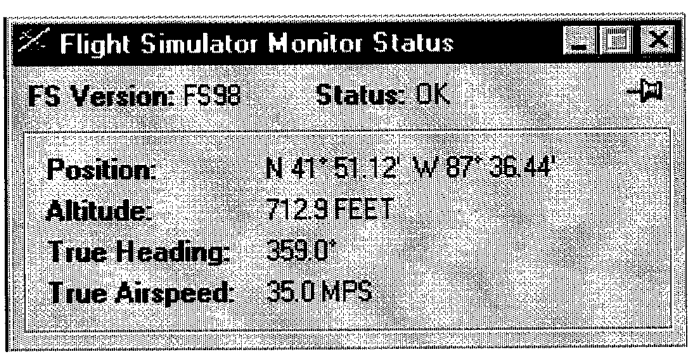



**Figure 12 Flight Simulator Monitor Status Display**

This screen will provide the WGS-84 converted data for use by the Terrain Avoidance System, Position Integrity Tactical Display, and any other suitable equipped applications. Because we have designed GPS MON and Flight Sim Mon to be fully compliant with Microsoft's Distributed Component Object Model (DCOM) specifications. This means that the application which use the services do not necessarily have to be on the same computer, but can be anywhere on the same TCP-IP enabled network (including Ethernet, Wide Area Networks, and across the Internet.)

## D.4.9.2.3. TERR AVOID

The GPS-Based Terrain Avoidance system includes two small windows as a part of the graphical user interface. The TerrAvoid window, shown below on the left maintains a continuous display of the color-shaded terrain for 60 NM around the aircraft. The Flight Mode Checks window, shown below on the right, provides all the text-based information, including GPS navigation data, and the status of the 6 warning modes.

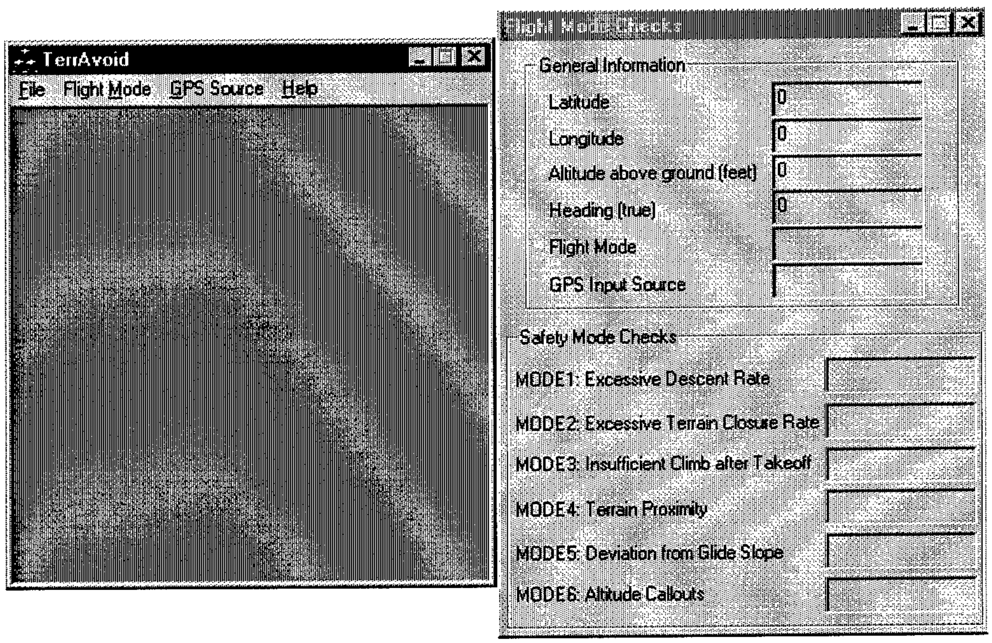



**Figure 13 TerrAvoid Displays before Initialization**

After starting the program, select, File, Settings to open the following dialog box:

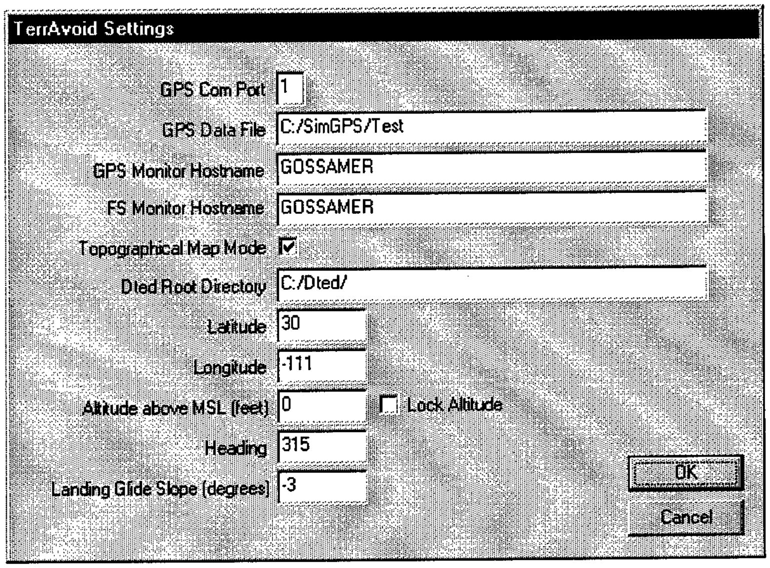



**Figure 14 TerrAvoid Setting Display**

The TerrAvoid setting dialog box allows the user to specify all of the initial parameters required to run the application. Here is the detail description for each field:

| | |
|---|---|
| GPS COM Port | Selection of the hardware computer communication port |
| GPS Data File | Location of the file which will be used for point by point simulation testing. This file is a text file that includes a new waypoint on each line. Each waypoint includes the latitude, longitude, altitude, time in milliseconds until next waypoint, and heading. The fields are tab delimited. |
| GPSMonitor Host Name | Specifies which computer on the network is running the GPS Monitor program. |
| FS Monitor Host Name | Specifies which computer on the network is running the FS Monitor program. |
| Topographic Map Mode | When check, provides high-resolution color shading of the terrain. |
| Dted Root Directory | Specifies the location of the top-level subdirectory of terrain files. |
| Latitude | Allow the user to specify the latitude of the display when using the test mode. If GPS or FS is providing the navigation information, this field will update whenever the dialog box is open. |
| Longitude | Allows the user to specify the longitude of the display when using the test mode. |
| Altitude above MSL (feet) | Allows the user to specify the altitude of the display when using the test mode. |
| Lock Altitude (check box) | Allows the user to override the GPS or FS provided altitude. We use this mode when performing testing of the system using a ground vehicle but wish to simulate flying. |
| Heading | Allows the user to specify the heading of the display when using the test mode. |
| Landing Glide Slope (degrees) | Sets the desired slope down (negative) from the horizon for Mode 5 GlideSlope Warnings. Alerts are generated when the aircraft glideslope is more than 10 degrees different from this value. |

**Figure 15 TerrAvoid Settings Mode Descriptions**

The Flight Mode drop down menu allows selection of the three operational modes of TerrAvoid. "Takeoff" mode reduces the safety zone to 2 NM and suppresses yellow terrain indication (only shades of red and green are shown.) Takeoff mode automatically transitions to "Free Flight" mode at 750 feet altitude. In Free Flight mode, the system shows terrain higher than the aircraft's altitude in continuous shades of red, with the brightest red indicating the highest terrain. Terrain which is anywhere from the aircraft's altitude down to 500 feet below is shown in continuous shades of yellow. Terrain which more than 500 feet below the aircraft altitude is shown in continuous shades of green. In this mode the safety zone is set at 30 nautical miles and is always in the direction of travel. The ellipse representing the safety zone is lightly shadowed on the graphic display. Ownship is always in the center of the display window and is shown by a white dot. "Landing" mode reduces the safety zone to 2NM and energizes the altitude callouts at soon as the aircraft is at or below 1000 feet AGL.

The GPS Source drop down menu allows selection of the navigation datastream. "GPS Unit" selects the GPS Monitor program to bring NMEA sentences in from the computers serial port. "Simulator" allows Flight Sim Monitor to extract WGS-84 corrected navigation data to be translated from Microsoft's Flight Simulator 98 program. "File" allows a pre-existing text file of waypoints to be read and executed as a simple and direct simulation file. "Test" instructs the program to use the user-defined lat, long, and altitude to be used as a starting point. The program then automatically advances at 50 feet per update at a fixed 315-degree heading. This equates to approximately 390 knots. The "heading" field under the TerrAvoid Settings dialogue box slews the safety zone around the aircraft to look in any direction.

The TerrAvoid graphic display and Flight Mode checks are constantly updated every 4 seconds in flight. The combined displays look the following, which was taken from and actual flight of an unmanned air vehicle flying towards the Suez Canal in Egypt.

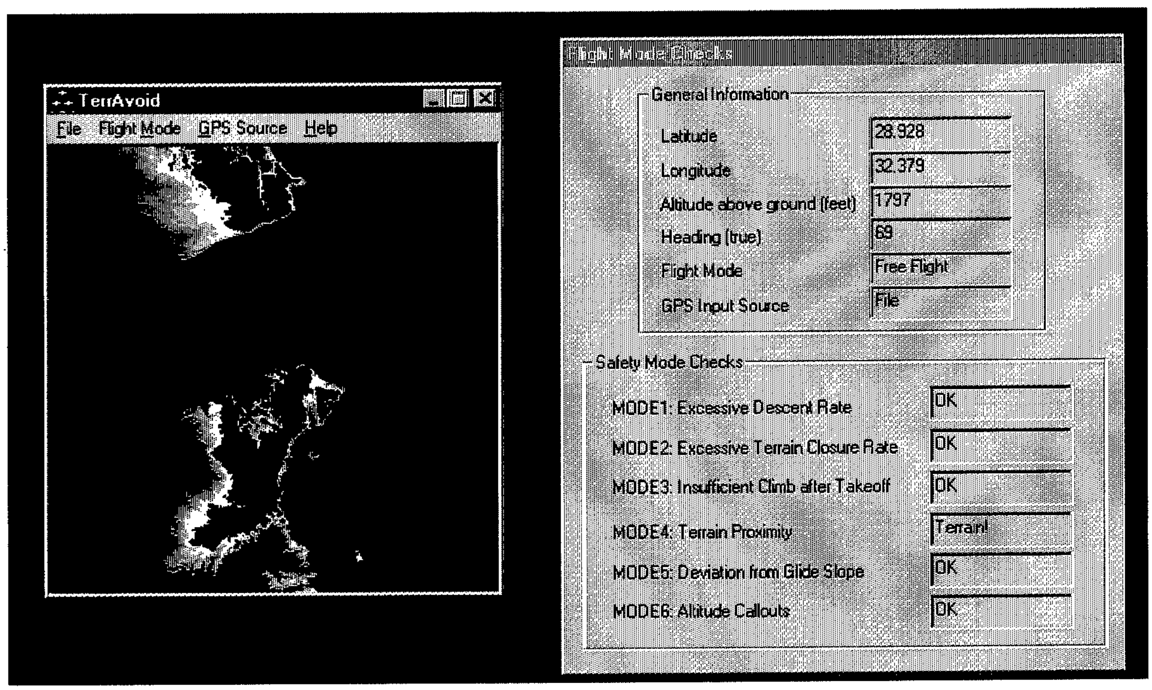



**Figure 16 TerrAvoid Displays from UAV flight in Egypt**

## D.4.9.2.4 Comparison of the Simulator Functions

To allow the user the maximum flexibility in pre-flight testing and simulation we built an internal waypoint simulator and designed an interface to Microsoft Flight Simulator 98 for more elaborate testing. The internal waypoint simulator is similar to what we designed for our Phase I effort in that it allows the user to specify a series of waypoints in a text file. Each waypoint contains a latitude, longitude, altitude, and velocity to get to the next waypoint. By designing these waypoints as a simple text file, any text editor

like the Microsoft Notepad can be used to generate, edit and manipulate the files. An option is then selected in the TerrAvoid operational menu which allows selection of the text file path and file name. We have already used this simulator to test many of the basic features of the program, including flight vectors from all points of the compass.

For more elaborate simulations we decided to interface the system to a professional flight simulator program which has been optimized to run on non-hardware-accelerated Windows computers. One of the most popular, feature rich, and inexpensive of these simulators is Microsoft Flight Simulator (now available in a 98 version for less than $50.) We contacted Microsoft to get the interface details to the positional variables in their program and from this we built a front end bridge to TerrAvoid. Uses can now conduct fly-throughs anywhere on the globe using Flight Simulator, taking off from over 3000 airports in the Microsoft library, and traversing over 3D scenery which is updated in real time on the screen. As the pilot maneuvers the plane, its latitude, longitude, altitude and navigation vector are fed to our terrain avoidance system and to our moving map system running on a separate computer. The computers are linked via Ethernet. The interface is built around the industry standard protocols of Active X/Object Linking and Embedding (OLE) and Distributed Component Object Modeling (D-COM). This mode of testing our software is especially useful in demonstrating the warning modes which are triggered on vertical descent rates such as "glideslope" and "failure to climb after takeoff" alerts.

In general, the internal waypoint simulator is better for testing a small number of precise terrain warning scenarios, while the Flight Simulator interface is better for testing long modulated and undulating flight vectors that would be too tedious to code into text files manually. Together the two provide 100% testing capabilities for all modes and features of our system. An added benefit is that these are also useful in giving non-canned "live" demonstrations to DOD officers of any geographic area on the globe.

### D.4.9.2.5 Non-Standard DTED Files

For global flight capability, we enhanced the terrain avoidance algorithms so they could access the non-standard DTED datafiles. "Standard" DTED level I files have 1200 x 1200 elevation postings at 3 arc second, 100 meter spacing. The "standard" DTED I is only arranged for latitudes between 50 degrees south to 50 degrees north (roughly the northern border of the CONUS.) From 50 to 70 degrees (north or south), the longitude lines begin to converge rapidly and the data is put in files which are still every 3 arc seconds in latitude, but are now every 6 arc seconds in longitude. This means a DTED cell in this region has 600 data records (longitude profiles) with 1200 data values (latitude values) in each record. Similarly DTED for 70-75 degrees N/S have 400 data records with 1200 data values each. And DTED for 75-80 have 300 with 1200; and 80-90 have 200 with 1200.

We have now incorporated a "universal" access feature with our algorithm so that it can read DTED level I data anywhere on the globe.

## D.4.10 TEST PROCEDURES

### D.4.10.1 Overview

This section was designed to capture our complete test regiment in testing the GPS-Based Terrain Avoidance System. We will begin by describing the "test philosophy", which is the overarching framework under which all testing was conducted. Next the "test plan" will be discussed which matrixes the system specifications with a test array. Then we will describe the "test sequence." This sequence shows how we progress through our many plateaus or levels of testing protocol, which started with simple laboratory testing of simple waypoints one at a time, and ended with a complete fully audited flight test procedure which was executed at the FAA Technical Center as witnessed by over a dozen FAA officials.

In this section the reader will find the test plans for all the informal laboratory tests, the ground tests, the internal Orange County flight tests, and the St Lucia attempted flight tests. In addition the test results for all these activities will be reported in this section. In Section D.4.11, you will find the test

procedures for the more formal witnessed flight test in Atlantic City, as well as all the test results and witness comments.

### D.4.10.2 Test Philosophy

The fundamental framework for testing complex system rests on the mathematics of "eigenvectors". Technically speaking, eigenvectors are the superset of orthogonal variables that together span the entire n-space of interest. In more normal language, we say that by determining the eigenvectors of a system, we are identifying all of the ways the system should be tested piece by piece to insure that the whole is stressed without leaving out any critical conditions.

Generically, a complex system may be thought of as operating, at any one time, at a single point along three axes of action: 1) the state of the operating modes, 2) the degree of dynamics, and 3) the degree of coupled interaction. The operating mode axis represents the collection of all the functions performed by the system. The Static-Dynamic axis represents the way the system performs as it is presented with a greater and greater number of decisions to make in real time. Finally, the uncoupled components-coupled system axis represents how many at a time are the functions being exercised. If we use a Cartesian-like coordinate system to display these three independent concepts, we might visualize the testing domain as looking like the following:

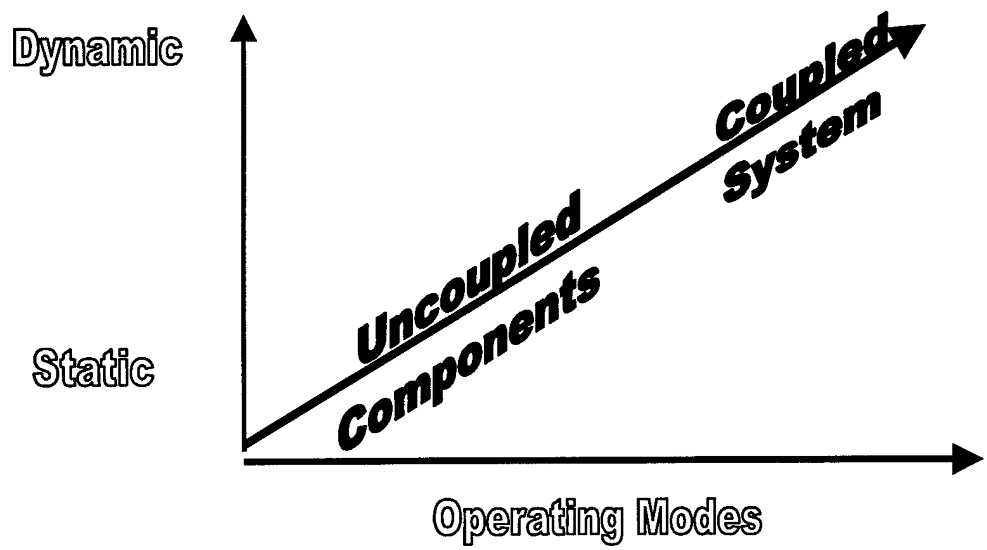



**Figure 17 Dimension of Complex System Testing**

This fundamental representation for viewing dynamic is the most useful point for establishing the generalized test criteria. Because the axes are orthogonal, testing along one dimension does not pertebate the other two. For example we can pick one operating mode as an uncoupled component and test it on the range going from static to dynamic, and know that this is a different test than testing a different operating mode in the same manner. This is why we first identify the "othogonal"eigenvectors of the system. Otherwise we might end up testing thousands of conditions and miss some critical component or mode. The following test plan will apply this fundamental eigenvector testing philosophy.

### D.4.10.3 Test Plan

The GPS Terrain Avoidance system has six operating modes, which were modeled after the required functions specified by the FAA in their TSO C92c. This same six-mode approach carried over into their most recent draft release, TSO 151. In general the terrain avoidance modes are:

| | | |
|---|---|---|
| Mode One | Excessive Descent Rate / Sinkrate Warning | To warn when the aircraft's descent rate is excessive with respect to the height above the terrain. |
| Mode Two | Excessive Closure Rate to Terrain | To warn when the aircraft is closing toward terrain at an excessive speed. This mode adds the component of speed to the normal terrain warning computations. |
| Mode Three | Excessive Descent After Takeoff | To warn when the aircraft's descent rate is excessive during takeoff or missed approach. |
| Mode Four | Insufficient Terrain Clearance | This is the "normal" operating mode for the system. It's basically the same as Mode Two, but applies to normal flight speed regime. |
| Mode Five | Inadvertent Descent Below Glideslope | To warn the pilot of "unreasonable" aircraft pitch angle during landing mode. |
| Mode Six | Altitude Callouts | To queue pilot situational awareness on landing. |

**Figure 18 TerrAvoid Mode Summary**

A more detailed description of each mode may be found in section D.4.8 Software Requirements.

For each mode, we must test the system in for both static and dynamic performance. An example of a static test for Mode four is to place the airplane stationary at 30.0001 NM away from a mountain, and then precisely move the aircraft one increment so that it is 29.9999 NM away and generates a terrain alert. An example of a dynamic test is to fly the across the same threshold at a normal 320 knots.

Finally we must test each node independently, being as selective as we can to not trigger the other modes, while also watching for falsely triggered alerts. Then we concatenate the modes one at a time in a spiral sequences leading up to a complete and thorough test of the "coupled system performance".

Because TerrAvoid is a complex computer application, we had to built in unique test tools to help identify how the system would perform across the various combinations of individual tests cases (the "eigenvalues" of the system, which lie along some well-defined position along the eigenvecotor axes.). These test tools are described in more detail in section D.4.9, Operating Instructions, but in summary, they are represented by:

1. The "Single Vector Test Mode", where the aircraft is placed at a desired point and flys in a repeatable path upwards and across the terrain.
2. The "Data File Test Mode", where individual waypoints and fixed velocities and heading are maintained exactly on each leg between the waypoints.
3. "Flight Simulator Mode", where more realistic and dynamic flight characteristics are modeled.
4. "Ground Test Mode", where a real GPS unit in a real moving vehicle generates the horizontal navigation points, the user plugs in the simulated altitude depending on the values of the local terrain being driven through.
5. "Flight Test Mode", where real GPS parameters are used, at a real dynamic update rates, and with all terrain avoidance functions operating as a coupled system.

Observe that we can be very precise when using test tools 1) Single Vector and 2) Data File but we can't be realistically dynamic. When we employ test tools 3) Flight Simulator and 4) Ground Test we can approach realistic dynamics, but we necessarily give up point by point precision. A broad and comprehensive test sequence, like the one that we adopted on this SBIR program, blends all the test tools in an upward spiraling plan of attack, so that each aspect of the complex system is tested for sufficient compliance with specification.

## D.4.10.4 Test Sequence

The test sequence for verifying TerrAvoid compliance with our specification started with using the Single Vector and Data File test tools on a variety of canned test situation we identified during our Phase I effort as being critical inflection points of the system. During the Phase I effort, the testing focused primarily on the laboratory testing of the underlying algorithm called Adaptive Real-time Altitude Detection, or "ARAD." For that effort we performed over 50 tests using single waypoints to "gently walk up to a trigger point", observe the system behavior, and verify the correct response was given. During Phase I, those tests encompassed many terrain warning triggers for the mountains around the Santiago Peak, which is one the highest mountain peaks in the Cleveland National Forest, and located relatively close to our offices in Irvine.

For this phase II effort, we duplicated a selective sample of the Phase I laboratory tests using both the Single Vector and Data File test tools. While the ARAD approach is essentially unchanged from Phase I, we just wanted to make sure that the newly coded algorithm performed identically as before.

Next we made extensive use of the Flight Simulator test tool and verified the more dynamic aspects of the system performance at a variety of sites around the world. Since the underlying program, Microsoft Flight Simulator 98, has airports modeled on all the continents, we practice runway takeoffs and landings on a global basis. Through our Flight Simulator Monitor interface, the WGS-84 converted coordinates were always available for cross correlation to published NAVAID information. NIMA put us on distribution for the Digital Aeronautical Flight Information File (DAFIF), which is updated every 56 days, and this served as the truth database for all our airport and runways tests.

Next we made several Ground Tests at the base of several mountains, with user inputted altitudes which simulated flight at appropriate levels to trigger the different terrain avoidance alerts. The purpose of these tests was to completely test out the GPS hardware and GPS Monitor, our software interface program. We needed to place a lot of emphasis on these tests, since out GPS units were completely different from out Phase I project. For the Phase II effort, we used both the Rockwell Portable Lightweight GPS Receiver (PLGR +96) as well as the newer Rockwell Special Operations Lightweight GPS Receiver (SOLGR). Both units were keyed to operate in P (Y) code mode and had a repeatable accuracy of 12 meters horizontal and 16 meters vertical. The ground tests gave us a chance to put both units through the complete cycles of cold start, satellite acquisition, GPS fix and standby status. We needed this experience so we knew how much time it might take on a flight test if we needed to do a cold start in the air.

Next in the test sequence came several flight tests, where we tested the end to end coupled performance of the complete system as it was automatically cycled through all its operating modes. These flights are covered in the following sections. The purpose of these flight tests was to closely match the actual conditions facing a pilot in a series of close encounters with CFIT conditions. The final flight test which served as our acceptance test was performed at the FAA Hughes Technical Center in Atlantic City and was witnessed by over a dozen FAA officials. This flight test is covered in Section D.4.11 Acceptance Test Plan and Results.

## D.4.10.5 R44 Helicopter Flight Test

On January 7, 1998 we conducted a full-scale flight test of the GPS-Based Terrain Avoidance system (TerrAvoid) and the moving map system (Position Integrity Tactical Display). This was done in a four-seat Robinson R44 helicopter which took off from and landed at John Wayne Orange County Airport. The attached pictures show this agile aircraft with our laptop computers in both the front and rear seats. Kimberly Dubbs, Dr. Kent Madsen and Robert Severino conducted the test. The next picture is a screen shot taken right after takeoff from the helipad. The TerrAvoid windows are top left and bottom left. The TerrAvoid graphic depicts a sixty mile view of the terrain, most of which is above us (shown in red). Yellow indicates terrain from our altitude down 500 feet, which is everything else. A view of the TerrAvoid Mode Checks reveals our altitude at 146 feet AGL. Mode 4 alert is warning of terrain in the safety zone.

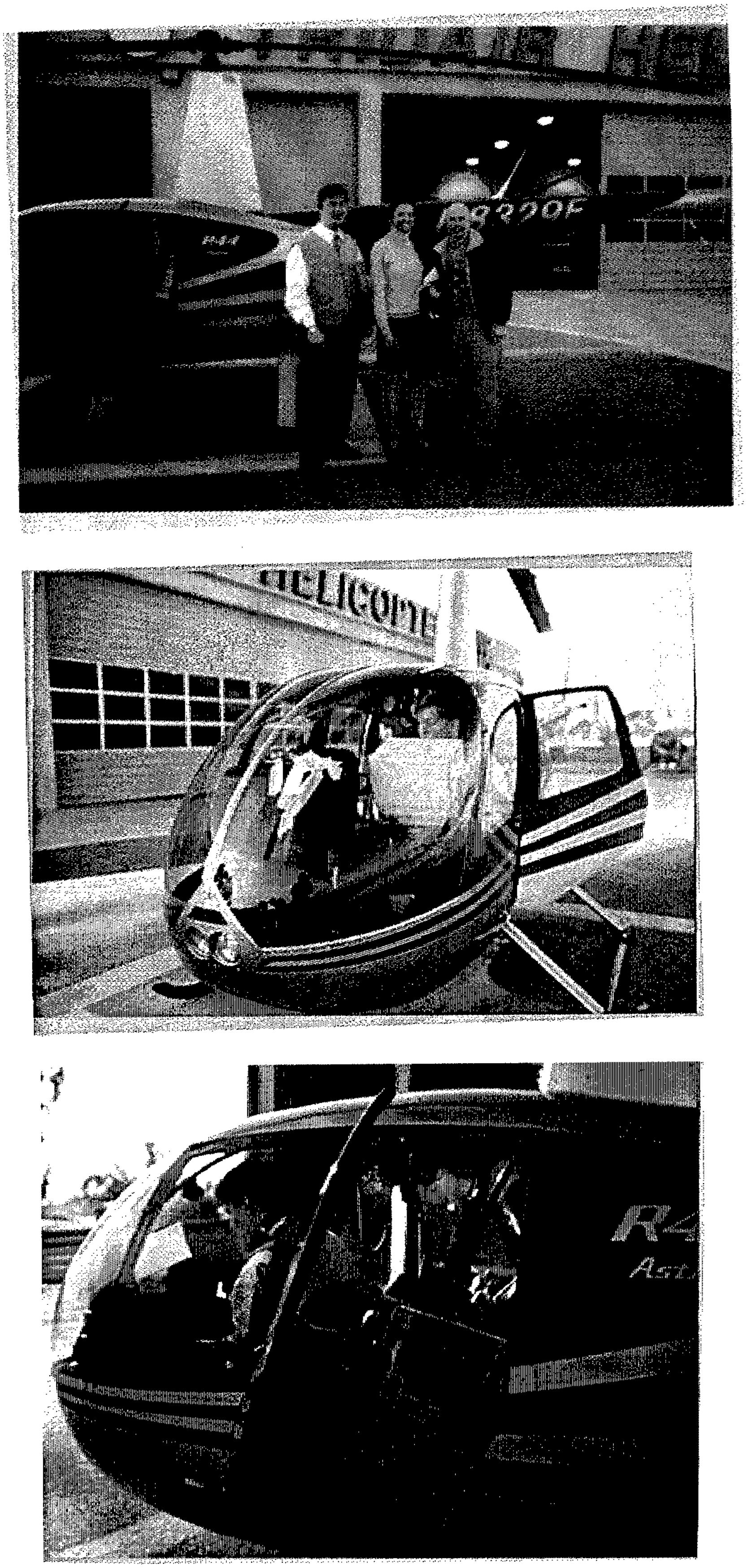
The Position Integrity moving map application is shown in the other four windows. The center top window is showing a pseudo-color shaded relief of the DTED terrain, at about the same scale as the TerrAvoid window. Santiago Peak (at 5280') is shown as the yellow mountain to the left in that window. The upper right window shows our position on a 1:250,000 scale USGS topographic map. The center

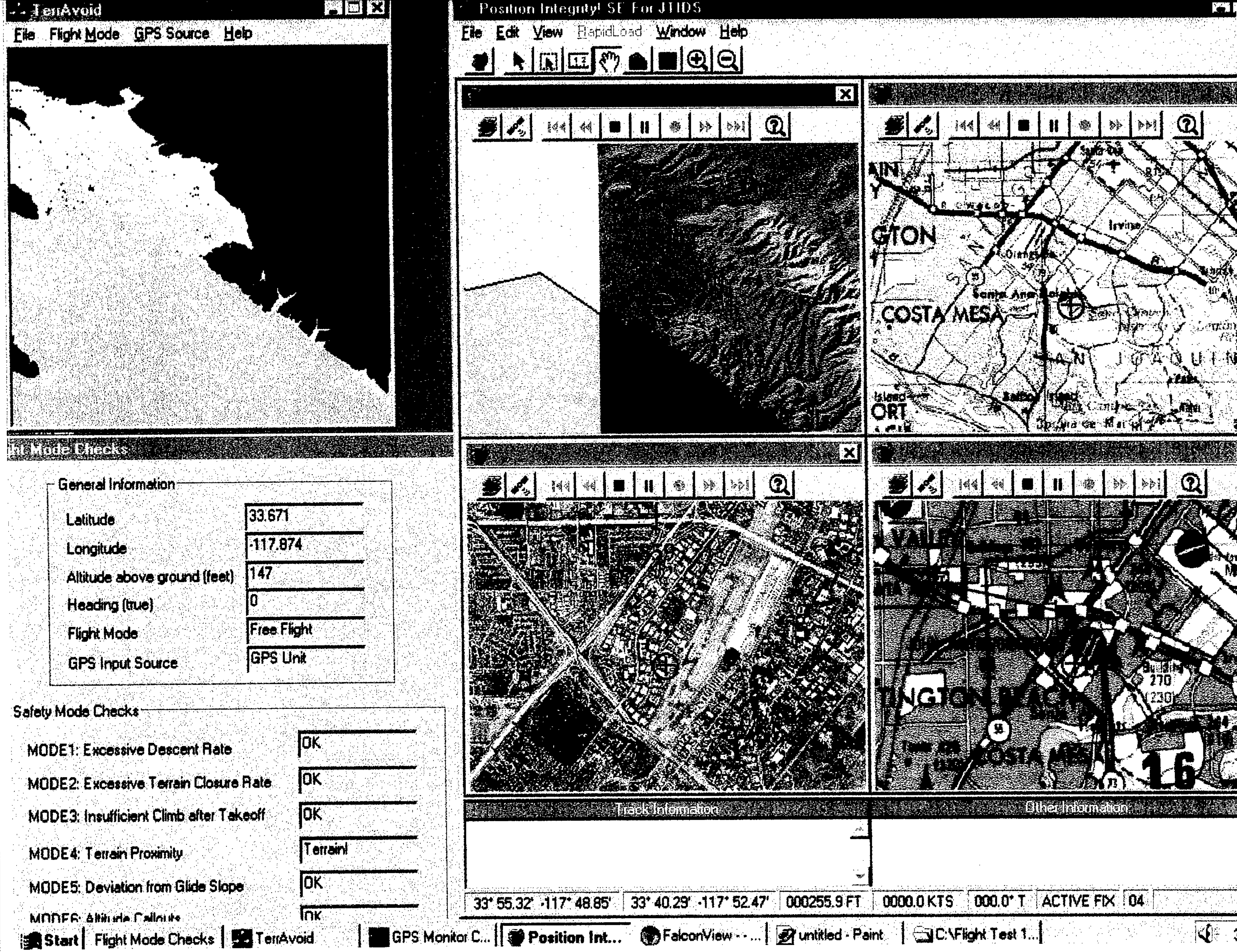
bottom shows our position on commercial photo-imagery, with the airport in bright white. The lower right window shows our position on a NIMA ADRG 1:250,000 scale JOG-A digitized chart.

The next color illustration shows most of our GPS tracks for the flight. The dots are not contiguous because some times I was testing the GPS serial port, which precludes the track recording function. The airport is shown in the center left of the screen. The orange "bread crumbs" to the north and west are from our tests of Mode 2 and Mode 4 terrain warnings, while we flew towards Santiago Peak. We also tested mode 3 (Insufficient Climb after Takeoff) while we were climbing enroute to the mountain. The lower tracks show a separate test we conducted by starting at 5000 feet and descending on a simulated glideslope. This test verified the operation of Mode 5 (Deviation from Glideslope) and Mode 6 (Altitude Callouts).

All modes were found to be operational and triggered when they were required to provide an alert. In general the system worked as expected which validates our laboratory and ground testing experience. By way future improvement, we found the algorithms a bit too sensitive and so later in the year we scaled back the thresholds for warning to avoid nuisance alerts. For example, when testing Mode 3, if the GPS reported even one altitude that was lower than the previous point, the alert would sound. The next month, we incorporated some smoothing in our algorithms to allow some minor up and down movement without triggering an alert.

**Figure 19 R-44 Helicopter Flight Test**





TerrAvoid
File Flight Mode GPS Source Help
Flight Mode Checks
General Information
Latitude 33.671
Longitude -117.874
Altitude above ground (feet) 147
Heading (true) 0
Flight Mode Free Flight
GPS Input Source GPS Unit
Safety Mode Checks
MODE1: Excessive Descent Rate OK
MODE2: Excessive Terrain Closure Rate OK
MODE3: Insufficient Climb after Takeoff OK
MODE4: Terrain Proximity Terrain!
MODE5: Deviation from Glide Slope OK
MODE6: Altitude Callouts OK
Position Integrity! SE For JTIDS
File Edit View RapidLoad Window Help
COSTA MESA
Track Information
Other Information
33° 55.32' -117° 48.85'
33° 40.29' -117° 52.47'
000255.9 FT
0000.0 KTS
000.0° T
ACTIVE FIX
04
Start
Flight Mode Checks
TerrAvoid
GPS Monitor C...
Position Int...
FalconView - ...
untitled - Paint
C:\Flight Test 1...

"TerrAvoid" FLIGHT TEST IN ROBINSON R44 HELICOPTER ON JANUARY 7, 1998.

Terrain Alert tests aimed at Sandago Peak, especially Mode 2 and Mode 4


Vertical Descent test aimed at verifying Modes 5 and 6.

## D.4.10.6 King Air 200 Flight For ARO

On March 12, 1998 we conducted a flight test on a passenger King Air 200, leased from AMT Combs at John Wayne/Orange County Airport. This test was conducted to show representatives from the Army Research Office, Research Triangle Park, NC our progress on the program. Because of the intermittent El Nino weather conditions, we had to postpone this flight several times, until we were sure of experiencing Visual Flight Rules (VFR) operation throughout the flight. The witnesses of the test from ARO were Col. Ken Jones, Dr. Francis X. Hurley, (the Technical Lead on this STTR program), and Dr. Russell Harmon. Mr. Rich Fretz, our JPL scientist, also witnessed the test. Our internal team members included the same designers as for our R44 Helicopter flight test, including Dr. Kent Madsen, Kimberly Dubbs and Robert Severino. The pilot was Mr. Ted Hamilton from AMR COMBS.

We exercised all six warning modes of the terrain avoidance system and interleaved at least 8 different images and maps on the moving map display. Two Toshiba 7xx series laptops were identically configured with both the Terrain Avoidance and with the Position Integrity Moving Map Software. We used a common GPS Receiver, the Rockwell PLGR+96 to drive both computers. This was done with our GPS Monitor program, which runs on one computer and sends the navigation data to all other computers connected via the Ethernet. (In this case there is just the one other computer on the net.)

A third IBM 760 Thinkpad laptop computer served as the instrumentation computer. This PC was interfaced to a second commercial GPS receiver (Trimble SK8) with a DCI Differential DGPS receiver. The purpose of this system was to record all the navigation waypoints every 1 second for later analysis.

During takeoff and during the last phase of the flight test, we experienced the loss of operation of the system. During the flight we performed several interface tests and determined that the computers and software were operating perfectly, but the PLGR GPS unit driving the two Toshiba computers had outages where no navigation information was being provided. The outages lasted less than 4 minutes each (two outages.) For the week after the flight test we conducted a full and complete investigation into why the GPS outage occurred.

After extensive analysis we determined the likely problem. The first outage occurred for about 4 minutes directly during taxi and takeoff. Here is our analysis of what caused the GPS to stop outputting a complete navigation solution. When we loaded up the aircraft we were parked next to a tall hangar. We installed the GPS antenna on the dashboard of the cockpit and powered up all the systems. We were parked there for a good 20 minutes before beginning taxi and takeoff. During this time the GPS system could only see satellite vehicles (SV's) directly in front and the right of the aircraft. It could not see satellite behind us because the roof blocks those signals. It could not see any SV's to the left of us because of the tall hangar. The GPS unit therefore had lock on about 4 SV's but the position was not sufficiently spaced out to get a 3D-position fix. It therefore got a 2D-position fix and used the last available altitude (the airport is close to sea level). It goes into "Altitude Hold". As we taxied, I saw our position updating on the moving map and thought the GPS unit was performing normally. But the altitude hold being automatically engaged meant that no changes in altitude could be reported. When we lifted off the runway, the terrain avoidance system still thought it was on the ground and failed to update. Finally after a few minutes, a new 3D fix was obtained from 4 well spaced SV's and we were able to get both position and altitude information sent correctly to the software.

The second outage occurred when we executed a 180-degree turn to go back to the airport for landing. This time we lost all position fixes: no horizontal or vertical updates. A similar phenomenon was the cause. When we flew for almost fifteen minutes towards Santiago Peak and away from the airport, the GPS unit got used to the SV's being in front of the aircraft (in the northern sky). It could also get signals from SV's to the left and right of the aircraft. When we turned around and headed south, the SV's that the GPS unit was used to seeing were now being masked by the fuselage. It had to now re-acquire SV's in a different part of the sky. This re-acquisition took about four minutes. We landed with full 3D fixes being communicated in real time.

The other GPS related problem we had was with the DGPS receiver which was being used to feed a correction signal to the commercial Trimble GPS unit running our data recording computer. While we could get a DGPS signal on the ground intermittently, it was not reliable enough during flight. The net effect was not drastic—it just meant that the commercial Trimble GPS unit was reporting C/A code precision signals, which are only good to +/- 100 meters or so. The Trimble never the less received and processed signals throughout the flight.

The reason we never had these GPS related problems in our January R44 helicopter test is that the antenna was mounted high in the cockpit under the plexiglass dome/canopy and therefore had excellent visibility to all satellites.

In any event, for most of the King Air flight, when the GPS unit was performing well, the Terrain Avoidance system performed flawlessly. It sounded warnings when the alert threshold criteria were met and it ceased its warning when the CFIT condition was removed. The following pictures show the complement of King Air 200 and how the computers where configured on each side of the large cabin area.

The test plan for this flight is shown on the following page.

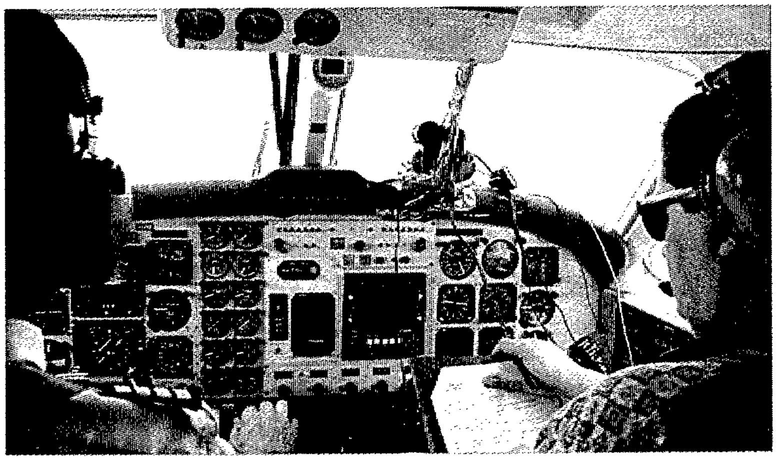
**Figure 22 King Air 200 Flight Test**

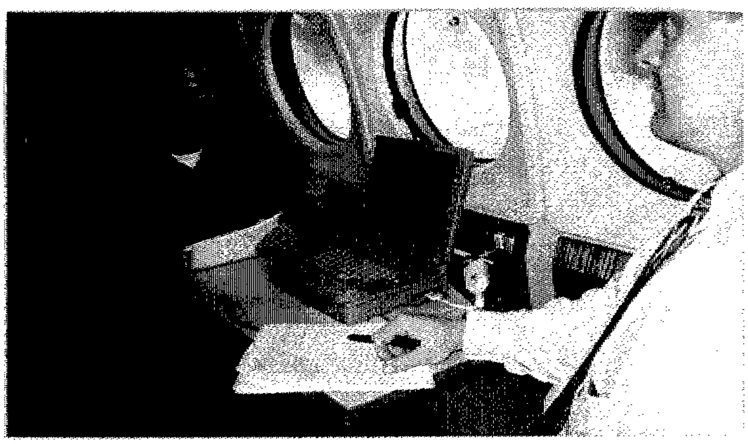
**Figure 23 Test Plan for March 12, 1998 King Air**

| | AIRCRAFT | SYSTEM | WARNING |
|---|---|---|---|
| 1. | Taxi and depart runway 19 to the south. | TakeOff | |
| 2. | Climb to 500 ft. | | |
| 3. | Gently drop to 450 ft. over six seconds. | | MODE 3: Insufficient Climb after takeoff |
| 4. | Climb to 700 ft. | Auto transition to Free-Flight | |
| 5. | Climb to 2500 ft. and turn left to heading 180. | | |
| 6. | Gently Drop to 1500 ft. | | MODE 1: Excessive Descent Rate |
| 7. | Climb to 5000 ft., Turn left in 10 degree increments dwelling about 10 seconds at each heading When heading is about 45 we will aimed at Santiago Peak | | MODE 4: Terrain Proximity |
| 8. | Turn left to heading 0 | Mode 4 clears | |
| 9. | Turn right to heading 45 or aim at Santiago Peak | | MODE 4: Terrain Proximity |
| 10. | Turn right to heading 135. | Mode 4 clears | |
| 11. | Turn left at heading 45 or directly at Santiago Peak | | MODE 4 Terrain Proximity |
| 12. | Climb to 6000, dwell about 20 seconds. | Mode 4 clears | |
| 13. | Climb to 6500 | Yellow terrain turns green | |
| 14. | Fly over peak at safe altitude towards March AF | | |
| 15. | Drop to 5000. Turn right to a heading of about 135, following I15 south towards Lake Elsinore | | MODE 4: Terrain Proximity |
| 16. | At Lake Elsinore, turn right to heading of about 220 and fly south through "notch" in ridge which follows highway 74 south. | Displays clear flight notch in peak. | MODE 4: Terrain Proximity<br>MODE 2: Excessive Terrain Closure Rate |
| 17. | After we fly through the mountains, turn right to heading of about 300. Climb to 6500 feet. | Mode 4 and 2 clears | |
| 18. | Over the 91 freeway at Anaheim hills, turn left to 190 and setup for southbound landing at John Wayne. | Operator selects landing mode | |
| 19. | Gentle descend at -3 degree glideslope | Operator selects landing mode. | |
| 20. | At about 4000 feet, change glideslope to -13 degrees | | MODE 5 Deviation from Glideslope |
| 21 | After 10 seconds change back to glideslope of -3 degrees | Mode 5 clears | |
| 22. | Descend to SNA, runway 19. | | MODE 6 Altitude callouts from 1000 feet down to landing in 100 foot increments. |

The cockpit was instrumented with GPS antennas and a video camera for recording the events of the flight. A laptop computer was placed on both sides of the cabin so that all witnesses could see the system in action. The two systems operating independently, which also tested the system's repeatability.

**Figure 24 In-Flight Pictures from King Air 200 Flight Test**





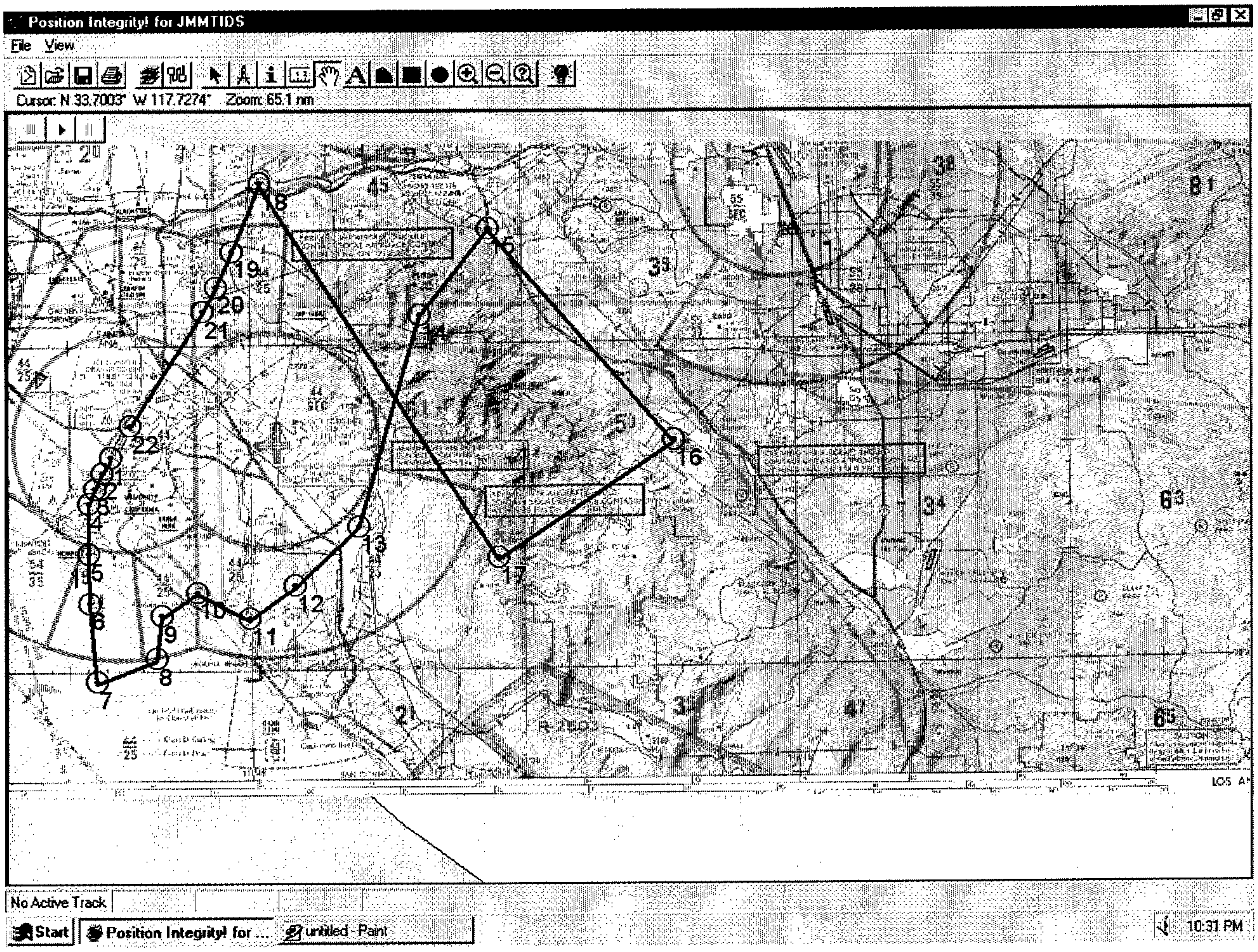
The following picture was taken just after we flew close to Santiago Peak in the rugged Cleveland National Forest. With TerrAvoid, the pilot said he would have felt safe making the trip even in bad weather. The bottom picture shows the complement of government witnesses, including ARO, JPL and our own team.

**Figure 25 Santiago Peak as seen from closest approach**

**Figure 26 ARO Team congratulating D&S after successful flight test**

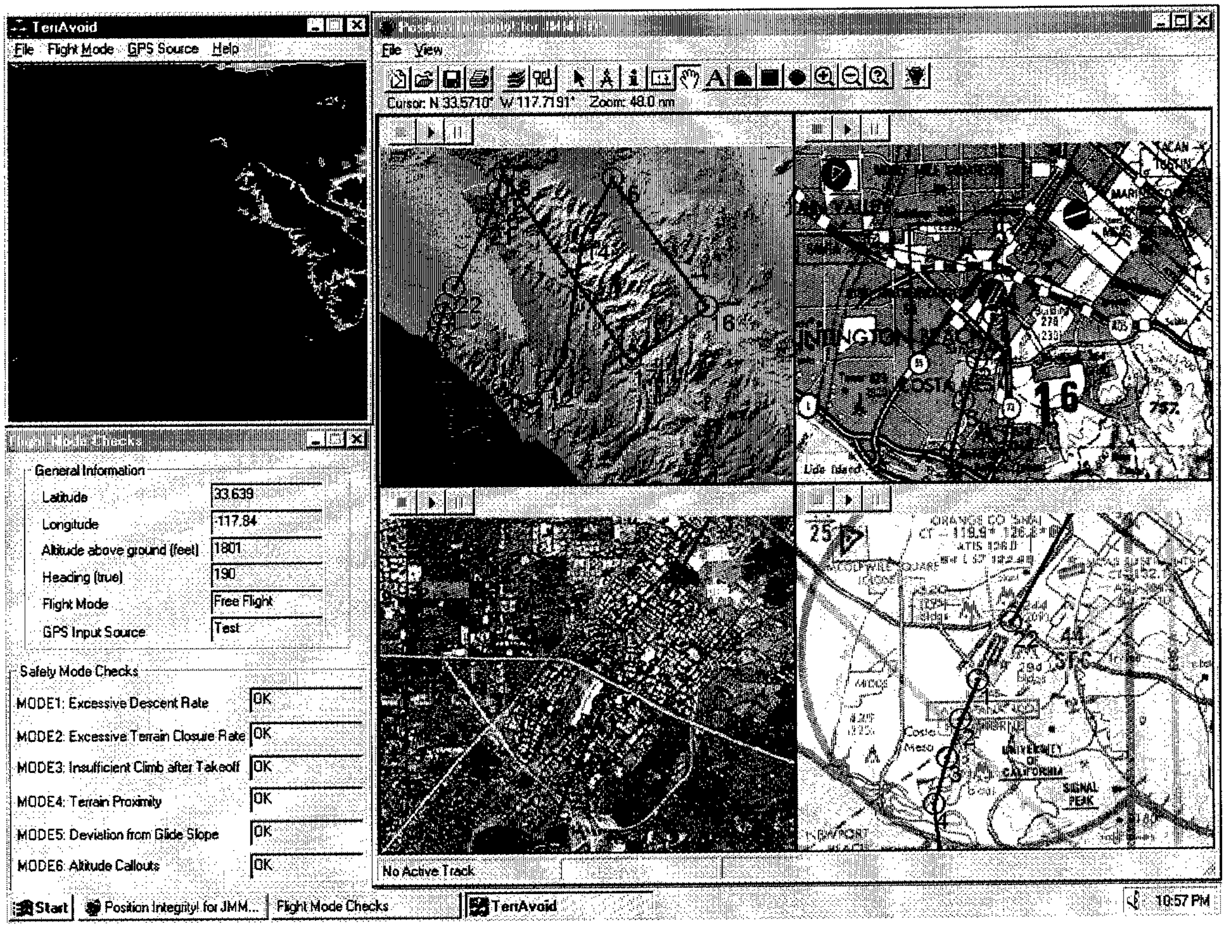
This screen shot was our test planning view. Before the flight we determined the 22 waypoints which would test all six modes of the terrain avoidance system in a fully automatic and coupled manner. Santiago Peak, which was the objective of most of the terrain "runs" is shown due north of Waypoint 17. TerrAvoid was sensitive enough that if correctly detected the peak as early as Waypoint 8, which was still out over the Pacific Ocean.

**Figure 27 King Air 200 Flight Test Waypoints and Route**



The following screen shot was taken in the air immediately after takeoff at 1800 feet. The red terrain shows that Santiago Peak is significantly higher that our altitude. The Position Integrity tactical display showed our position against a backdrop of four image windows: 1) pseudo-color shaded relief, 2) NIMA JOG-A, 3) commercial photo-imagery, and 4) FAA Terminal Area Chart. The intended route with all waypoints is shown in each window as a situational reference.

**Figure 28 King Air 200 Flight Test Screen Shot after takeoff**



## D.4.10.7 PC-12 Flight Test

During the summer of 1998, we received the new Rockwell Special Operations GPS Receiver (SOLGR). This unit was designed to meet the unique requirements of the Joint Special Operations Command (JSOC) who is acting as the research/development and acquisition office for the entire USSOCOM community. The unit is also going to the British special operations military. Dubbs & Severino, Inc. was the first commercial firm to receive the unit and we were a beta test site for its new firmware functions.
This P(Y) code unit has 12 channels, L1/L2 operation and uses the new 2.5Volt NightHawk GPS module. The net effect in performance over the Rockwell PLGR should have been decreased acquisition times, better dynamic performance, and longer batter life. We went to the GPS Joint Program Office at the Los Angeles Air Force Base to get both our units re-keyed with a 12 month GUV key. We then found and fixed a bug in the SOLGR firmware design, relating to the NMEA -0183 interface. It was then integrated with both our software packages.
In order to test the new GPS unit in conjunction with TerrAvoid, on September 14 we arranged for a six-passenger Pilatus PC-12 to conduct a full scale flight test in Orange County, CA. We spent 1 hour and 15 minutes flying around Santiago Peak, testing all the modes of the software on both systems. All TerrAvoid system functions worked flawlessly. As an additional GPS availability test, I tried to reset the SOGLR GPS to see how long it takes to re-acquire a complete 3D solution. After going in Standby, the unit came back up with full solution in less than 10 seconds. When I tried to turn it completely off, however, it took two minutes to gain a 3D solution from its "cold start." We do not expect to have to do any cold starts on future flight tests.

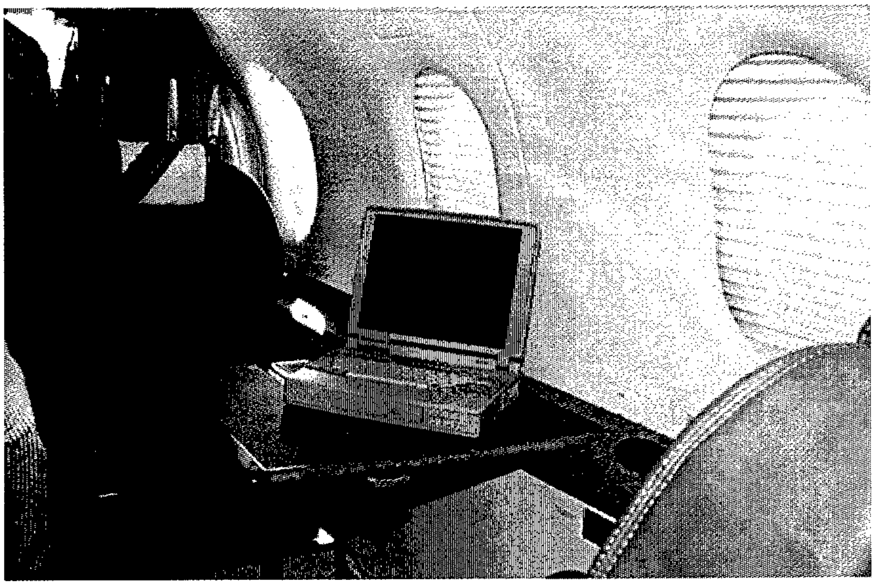
The day after our flight test, we added one more feature—the ability to record all GPS data at a 1HZ rate. This allows both systems to act as their own instrumentation computer, without the need for separate GPS receivers or computers. This feature is transparent to the user and may actually be useful to pilots in a commercial setting to help them understand their flying proficiency. After integration of this final feature, we ground tested both units again to insure that all systems were perfectly functional.

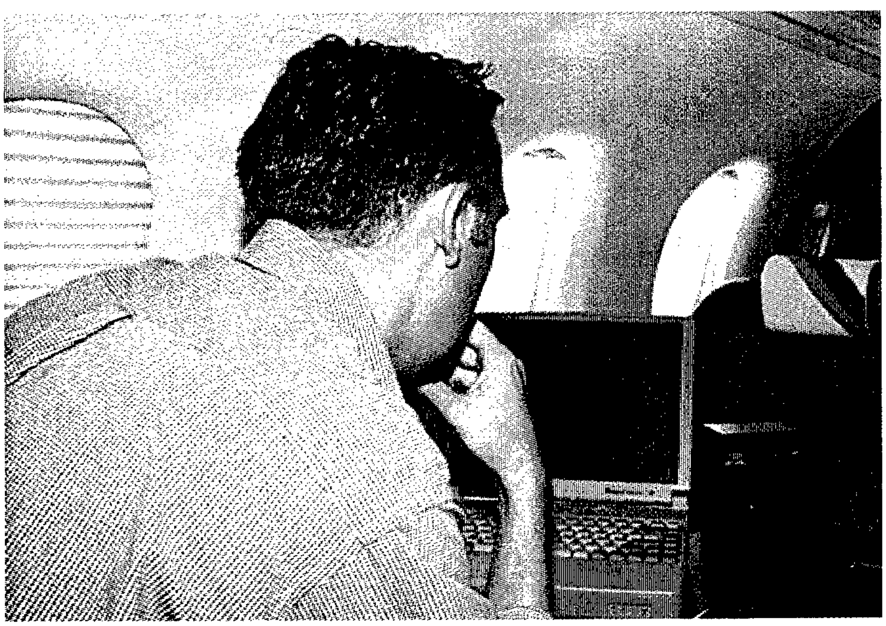
The PC-12 aircraft is shown below. It is a remarkably powerful high-performance single-engine workhorse that we used in Orange County and for our final acceptance test flight. Its raw climbing power allowed us to almost graze the mountaintops much more closely while maintaining an effective margin of safety.

**Figure 29 Pilatus PC-12**

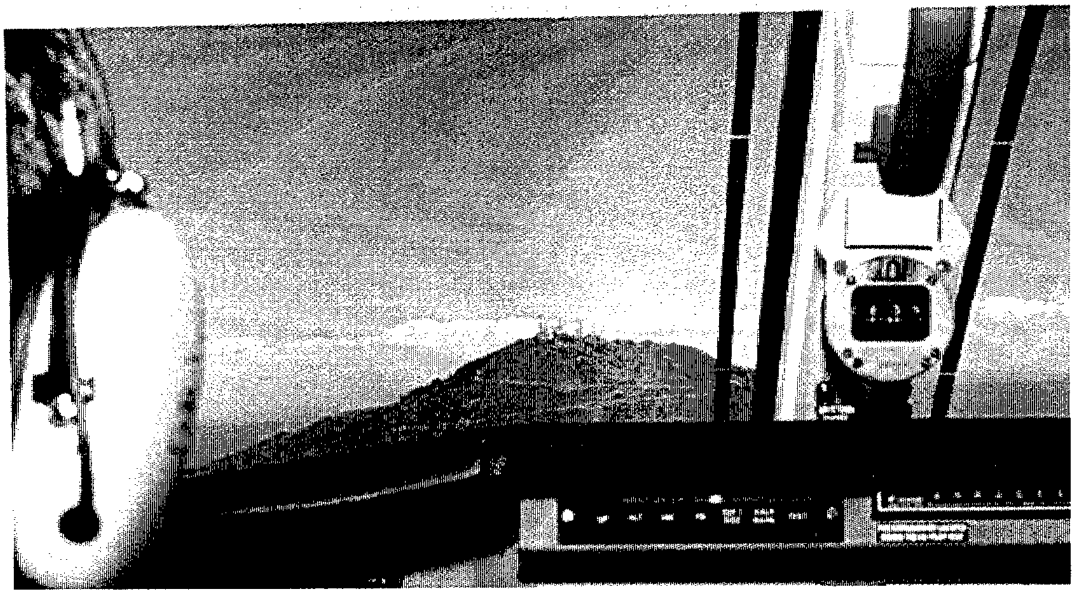
The following shots show how we placed the two Toshiba Tecra laptop computers on both sides of the cabin as we did with the King Air 200 in the previous flight test.

**Figure 30 Placement of Laptops for Pilatus PC-12 flight test**





As the following shots show, the PC-12 has sufficient power that we could safely almost graze the top of Santiago Peak, thereby putting TerrAvoid through it most exhaustive and precise flight test to date, especially with respect to terrain altitude sensitivity.



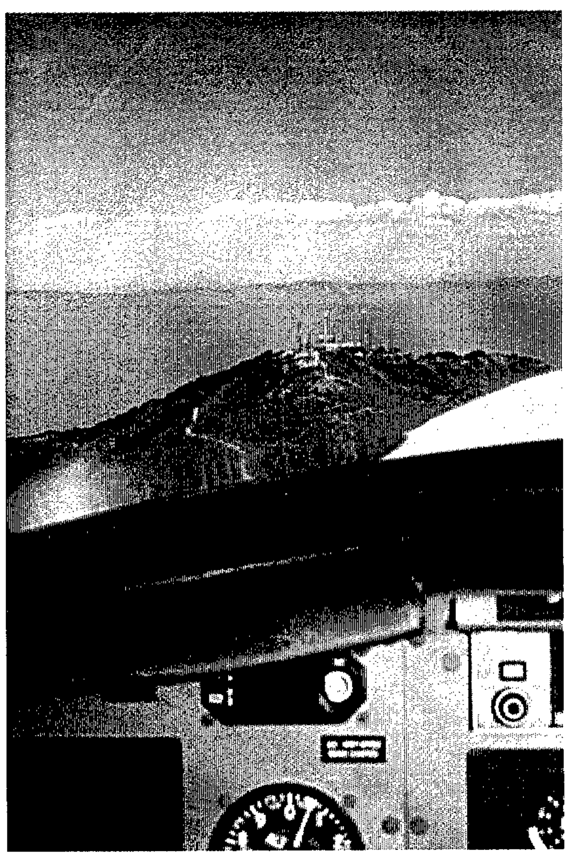


**Figure 31 Santiago Peak during Pilatus PC-12 flight test**

As the following shots show, we also extensively tested the landing mode, glideslope alerts, and altitude callouts. By interfacing one of the laptop computers with a high power audio amplifier, we could all hear the system annunciate the altitude callouts right down to touchdown at John Wayne/Santa Ana airport. In the lower picture Pilatus executive Dave Lawrence is shown with Robert Severino.

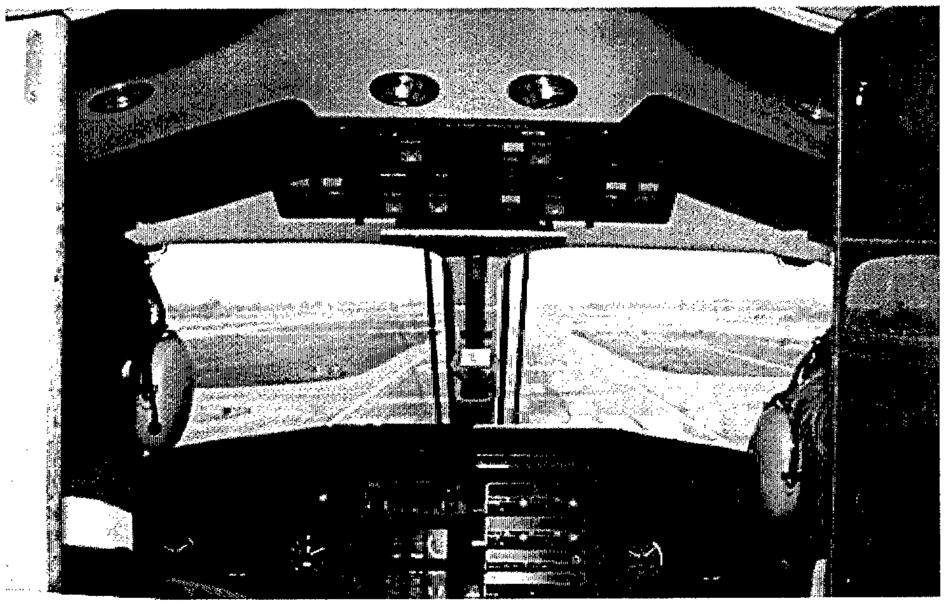


**Figure 32 PC-12 Cabin just before Landing**


**Figure 33 Pilatus Executive Dave Lawrence and Robert Severino**

## D.4.10.8 The CFIT Accident in Hawaii and the St. Lucia Flight Test

Sadly, during June 1998, world has experienced yet another tragic CFIT accident. We have interviewed the head investigator from the NTSB and the report reads as follows:

*NTSB Identification:* ***LAX98FA211***
*Nonscheduled 14 CFR 135 operation of OHANA AVIATION, INC. (D.B.A. OHANA HELICOPTER TOURS)*
*Accident occurred JUN-25-98 at MT. WAIALEALE, HI*
*Aircraft: Eurocopter AS-350-BA, registration: N594BK*
*Injuries: 6 Fatal.*

*On June 25, 1998, about 0930 hours Hawaiian standard time, a Eurocopter, AS-350-BA, N594BK, operated by Ohana Helicopter Tours, collided with mountainous terrain near Mt. Waialeale, Kauai, Hawaii. The helicopter was destroyed. The commercial pilot and the 5 passengers were fatally injured during the on-demand sightseeing air taxi flight which was being performed under 14 CFR 135. The flight originated from the Lihue Airport, Kauai, Hawaii, at 0843. The operator reported that the purpose of the flight was to provide the passengers with a 50 minute aerial tour of the island in accordance with a VFR company flight plan. Wreckage was observed scattered near the Waialeale crater's ridge at the 2,300 foot elevation on a 80-85 degree slope in deep foliage. The wreckage is not accessible from the ground.*

We learned the pilot was flying straight and level when he collided with the terrain at 2290 feet. We believe that our system could have avoided this accident. We first tried to get permission from the FAA to duplicate the preliminary portion of the flight in Hawaii, using the same AlphaStar 350 helicopter, only using our system to avoid the CFIT. Unfortunately, the FAA would not agree. We therefore attempted as faithfully as possible to re-create the flight vector taken by chartering a similar AlphaStar 350 helicopter, and using the similar topography of St. Lucia, Antilles. We will show the difference that having our GPS-terrain Avoidance and Navigation system could have made in saving those 6 lives.

After extensive terrain comparisons, we concluded that circum-navigating two large volcanic peaks called the Petit Piton and Gros Piton on the St. Lucia island would very closely approximate the CFIT accident in Hawaii. Because the FAA has no control over this island, we had much greater latitude in designing a robust flight test to our specifications. This flight test would have also represented a more comprehensive and dynamic flight profile than the several tests we have performed around the Santiago Peak in California. We wanted to use a helicopter because of its more precise control of above ground level (AGL) altitude during the various phases of the flight test. Several technical reasons pointed toward the ideal topographic relief of St. Lucia. First, the Pitons represent over 2000' of drastic vertical rise which occurs abruptly and close to the ocean shoreline. This means that we can make an over-ocean approach to dramatically capture the elevation differences. These drastic elevation differences were a factor in the fatal Controlled Flight Into Terrain (CFIT) accidents which claimed the several hundred lives at Cali, Columbia (American Airlines #965-December 94) and at Dubrovnik, former Yugoslavia (SecCoM Ron Brown-Air Force T43A in April, 95).

Secondly, because the islands airways are governed by British rules of flight, not American, the minimum altitudes that we can fly over populated and semi-populated areas are far less. This means we can test the system more fully in a terrain-closing mode in St. Lucia, than any where in the U.S. where FAA restricts us from flying any lower than 1500' above populated areas.

Third, we had never tested the GPS system outside the southern California environs. Different parts of the world present different GPS Satellite Vehicle constellation combinations. We deemed it important to make several tests in other parts of the world before we make claims as to this system's "global deployability".

In preparation for the flight test, we acquired very detailed 1:24,000 maps of St. Lucia, which we digitally scanned and ortho-rectified, and had converted to GeoTIFF for fast tiling. The Navy Space command found for us a Landsat multi-spectral image of the area, but it only covers the south part of the St. Lucia. Fortunately, this was the part we needed. We also obtained the latest DTED data, which covers all but the most northern tip of the island. We generated NIMA ADRG maps from GNC (1:5M) all the

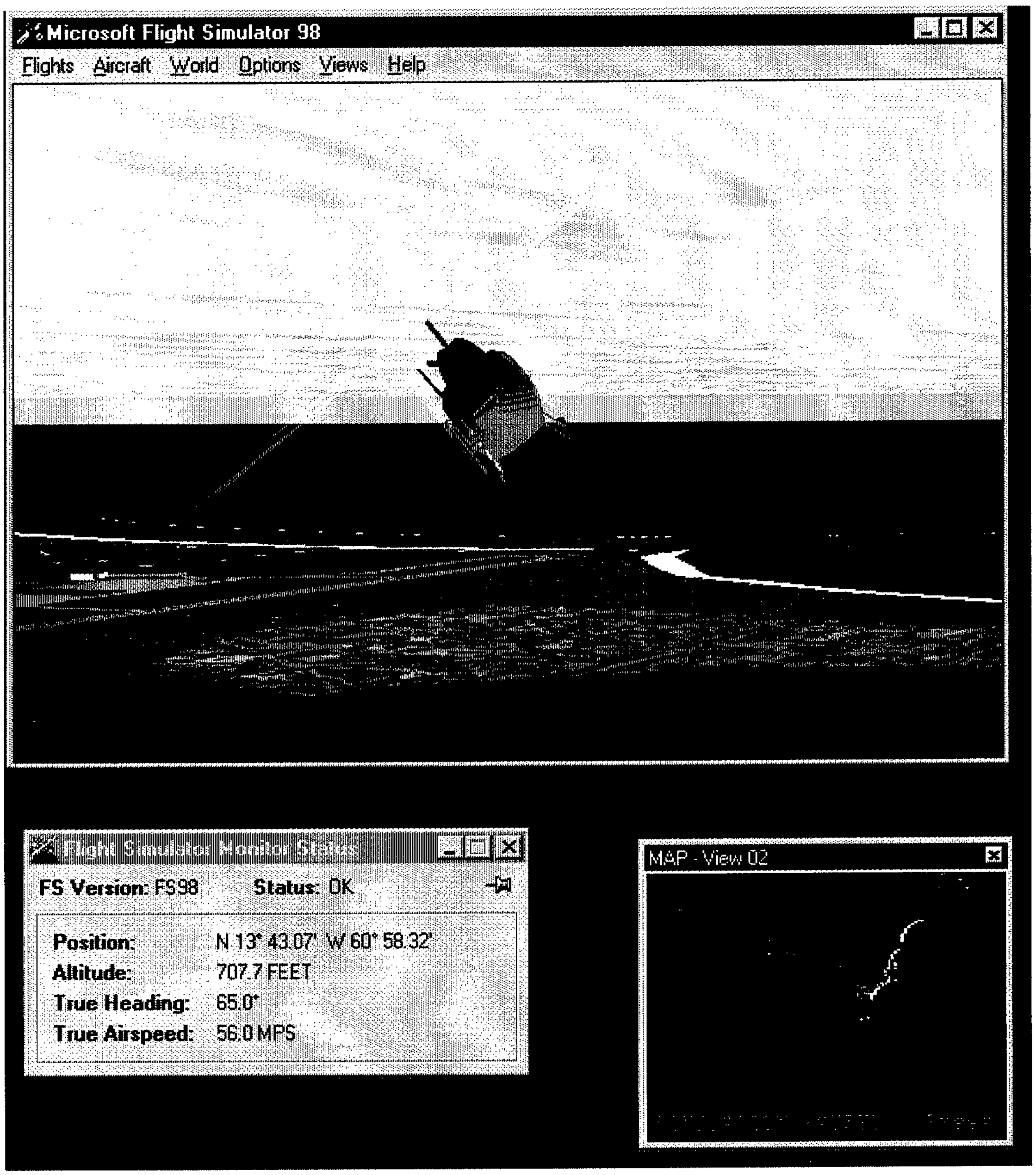
way down to JOG scale (1:250,000). All these datasets were loaded on our two Toshiba PC's for independent operation. The PLGR would have driven one PC and the SOLGR would have driven the other.

We used the expanded land feature databases generated by Microsoft for their Flight Simulator 98 "enhanced scenery pack". The screen shots on the following pages show the high resolution modeling we were able to do in our laboratory modeling the flight from Hewanora Airport to the Pitons.

Unfortunately, after landing in St. Lucia on September 18, 1998, Hurricane Georges unleashed its 150 mile per hour furry on the entire Caribbean area and effectively grounded all flights for our operating window of opportunity. So instead, we drove around the Piton peaks using the "set altitude" feature of TerrAvoid to simulate flight. We were able to verify the Mode 2 and 4 terrain alert warnings and were able to completely test our new GPS unit in a non-U.S. location. The field trip was good practice for our eventual final flight test in Atlantic City for the FAA.

Here FS98 and our Flight Simulator Monitor are being used in tandem to simulate flights around the Hewannora Airport in southern St. Lucia.

**Figure 34 Flight Simulator and FS Monitor Displays of St. Lucia**



This screen shot shows the level of detail we could extract from our simulation around the two Piton peaks. The larger of the two (Gros Piton) is shown on the right side of the right picture, while the Petit Piton is in the center. In the photograph at the bottom of the page, the scene was shot from the ocean leaving the Pitons reversed. Still you can see how closely the simulation matched reality.

**Figure 35 Flight Simulator View of St. Lucia Pitons**

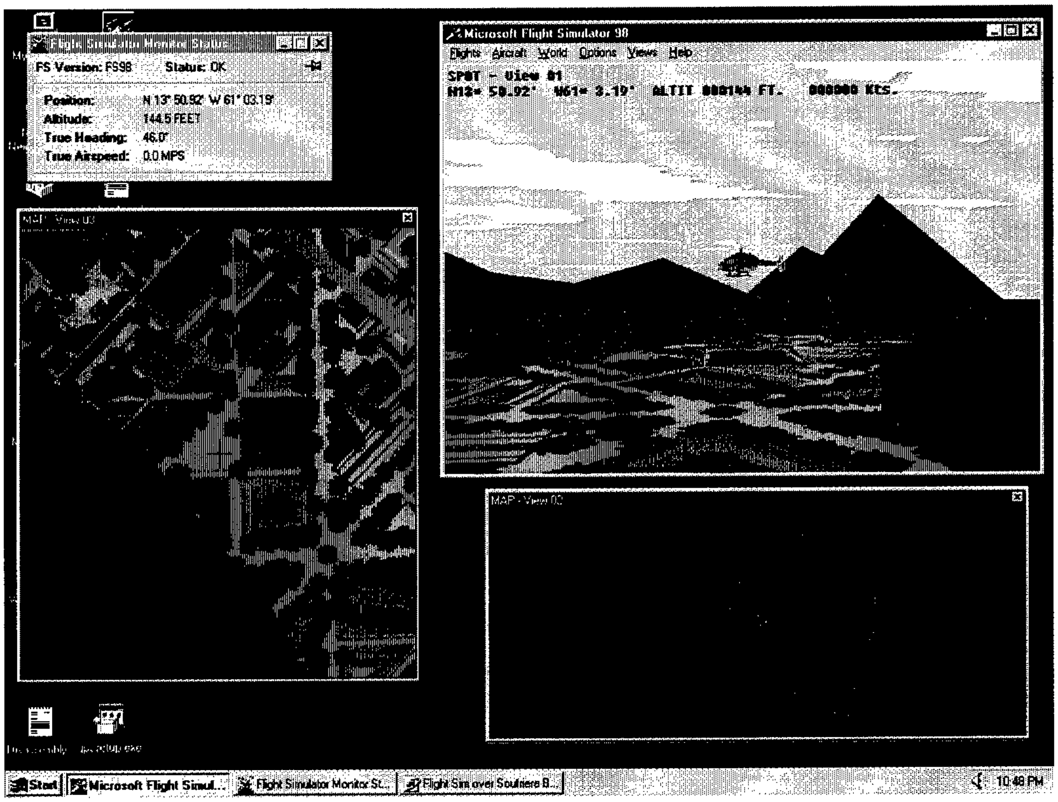
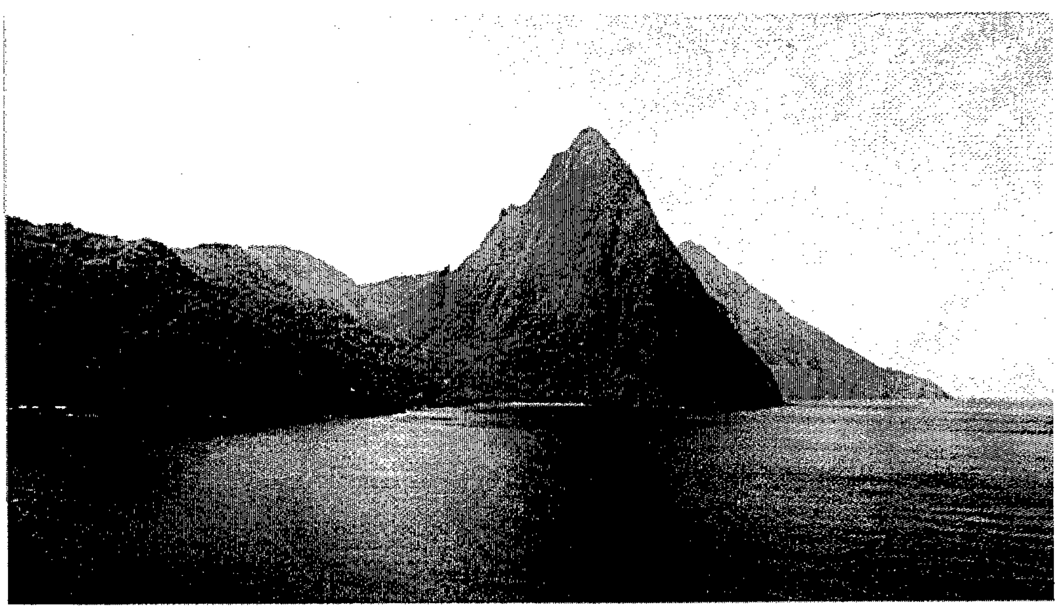



**Figure 36 Actual Pictures of St. Lucia Pitons**



On this page, the high detail of the British 1:24K topo maps is evident on the left screen, while the NIMA JOG-A is shown on the right. Below is an actual photograph taken of the Pitons.

**Figure 37 Map Displays of St. Lucia Pitons**

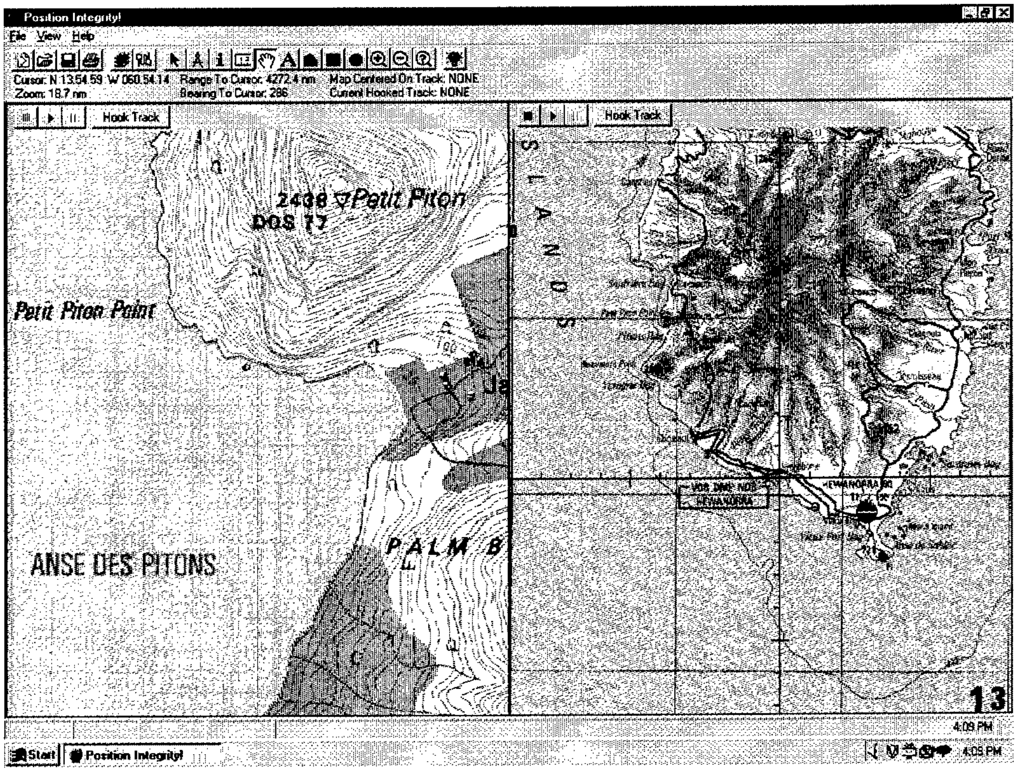
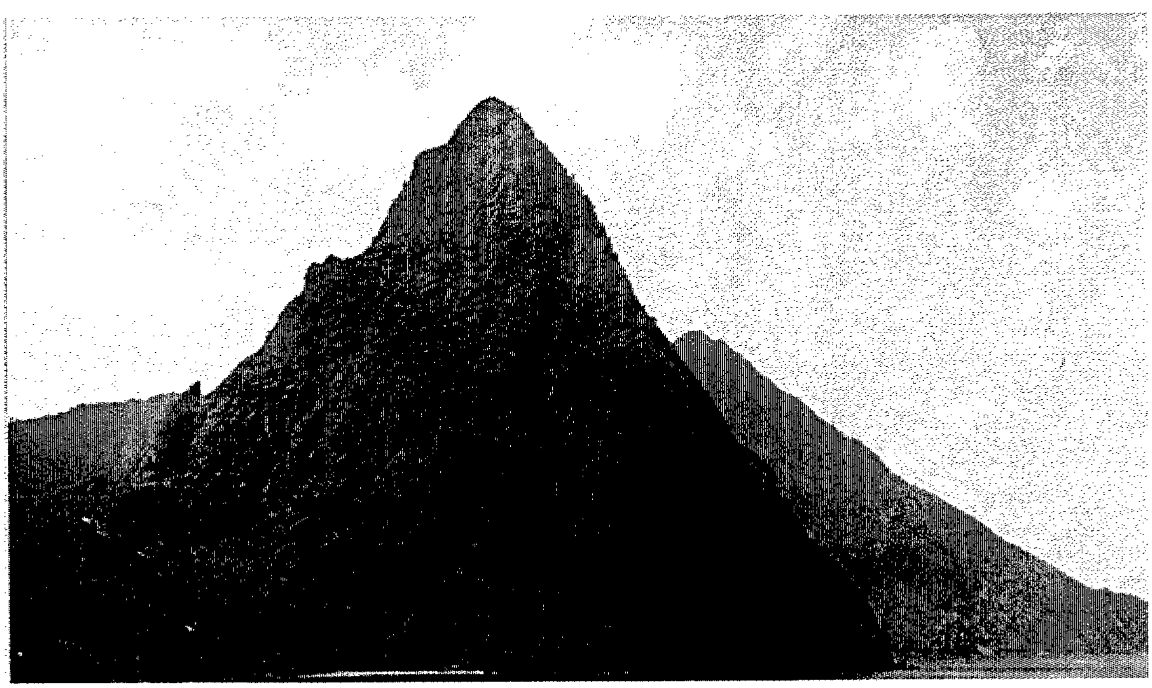



**Figure 38 Actual Picture of St. Lucia Pitons close-up**



On this page you see the TerrAvoid System and the Moving Map display illustrating enhanced situational awareness around the Hewannora Airport. On the terrain display, the red and yellow clump is St. Lucia. NIMA DTED coverage of the island does not include the northern tip and so TerrAvoid colors that area gray for "no data". The red clump at the lower end of the display is the island of St. Vincent to the south. The lower picture is NOAA representation of the destructive path of Hurricane Georges which took many lives in its wake that week.

**Figure 39 Integrated TerrAvoid and Position Integrity Displays from St. Lucia Ground Tests**

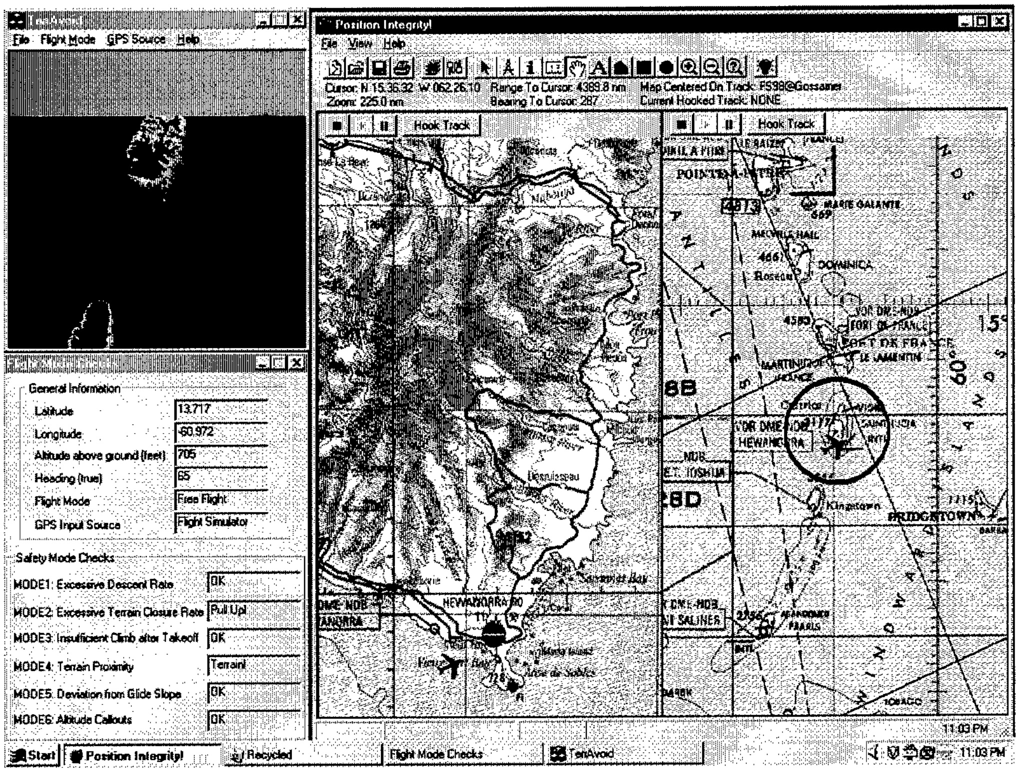
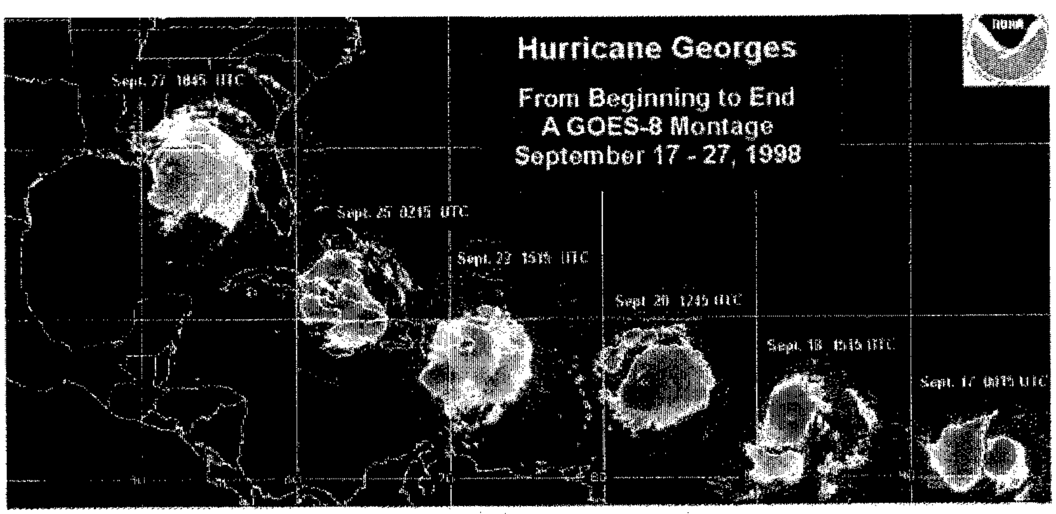



**Figure 40 Hurricane Georges track across the Caribbean**




With winds peaking at 150 mph, Georges blew across the Atlantic, Caribbean and the Gulf of Mexico in late September. This satellite montage features images gathered by the National Oceanic and Atmospheric Administration's Geostationary Operational Environmental Satellite No. 8, or GOES-8. (UTC is the international abbreviation for Coordinated Universal Time.)

## D.4.10.9 Summary of Laboratory, Ground and Flight Tests

For all tests conducted we found the GPS-Based Terrain Avoidance System performed per all specifications. We tested the eigenvectors for all system modes in both static and dynamic tests, and we tested individual modes by themselves as well tested the complete application as a coupled and interactive system. The problems we had with reliably sensing GPS navigation inputs was fixed with a more robust GPS receiver and better GPS antenna placement.

We then put the total system through two more final flight tests in front of FAA officials in Atlantic City. The plan and results of these tests is found in the next section, Acceptance Test Plan.

# D.4.11 ACCEPTANCE TEST PLAN AND RESULTS

## D.4.11.1 Overview

This section was designed to capture our final acceptance test of the GPS-Based Terrain Avoidance System. Described herein is the fully audited flight test procedure that was executed at the FAA Technical Center as witnessed by over a dozen FAA officials. While exhaustive in itself, this acceptance test was not the only flight test to verify proper system performance. The complete test regiment in testing the GPS-Based Terrain Avoidance System has a full test sequence and associated audit trail. This sequence shows how we progress through our many plateaus or levels of testing protocol, which started with simple laboratory testing of simple waypoints one at a time, progressed through many dynamic Flight Simulations and ended with many individual flight tests in California and St. Lucia. This was described in the previous section.

## D.4.11.2 Setting of Flight Test Facility and Guest Participation

The GPS-Based Terrain Avoidance System has been mostly funded by military SBIR and STTR programs from its inception. However, the Department of Transportation Volpe National Transportation Systems Center in Cambridge, MA and the Federal Aviation Administration Headquarters in Washington DC have also provided small elements of funding and more importantly have provided high levels of visibility to our project throughout these last five years. One particular product champion has been Dorothy Buckanin, head of ACT-300 at the William J. Hughes Technical Center of the FAA in Atlantic City, N.J. Ms. Buckanin arranged to host our final acceptance flight tests at the Technical Center. The arrangement was that we would provide the aircraft and all supporting logistics for the tests, while she would provide local FAA pilot expertise, a good deal of latitude in doing whatever we (safe) exercises we wanted to in the skies around New Jersey and Pennsylvania, and most importantly top level FAA executives to witness the flight tests. Several charter planes ferried FAA officials from the Washington DC headquarters to Atlantic City that day just for our flight test.

The day selected by mutual agreement was November 10, 1998. For our part, we charted the same PC-12 aircraft described in CDRL A005 for our Orange County flight test, and provided an expert test pilot that could stretch our system limits while still flying within reasonable safety guidelines. Having FAA officials on board for a "FAA qualified test flight" meant that the Air Traffic Control gave us "carte blanche" for flight maneuvering wherever we wanted to go. **The attached agenda highlights the activities of the day and the attendees present**. We started with a conference room presentation of our system capabilities and overall flight test objectives. This was followed by a presentation on the PC-12 aircraft capabilities and its suitability for doing our dynamic flight test. Following this was a technical question and answer period. This session was key because the presentation was being teleconferenced to FAA executives back at the Headquarters building in Washington, D.C. and they had a good deal of interest in terms of eventual certification of our system for use by the General Aviation (GA) and

commercial sectors for which they managed. In the following picture, Pete Sparacino, Head of AAR-201 is introducing Robert Severino.

**Figure 41 FAA Briefing at Hughes Technical Center, Atlantic City**

We began the first flight test at 11:00 AM and then to accommodate the balance of the witnesses who could not fit on board the first flight, we scheduled a second flight at 1:00PM. Both flights were very nearly identical in terms of path taken, terrain situations presented and altitude profile. Besides FAA officials, several Aerospace scientists were also invited to join us to round the technical breadth of the witness groups. Members from Mitre and Hi-Tec System were invited because they were providing on-site contractor support for advanced research and development architectures. Members from Orbital Sciences/Fairchild Defense Systems were invited to join because we are teamed with them in converting our Windows based software application into an embedded solution. This embedded system is planned to operate on Orbital's GPS loader, which is currently on thousands of Navy aircraft. In summary, the witnesses represented an excellent cross section of administrators, pilots, researchers, scientists and fellow avionics designers.

## AGENDA

### Dubbs & Severino Terrain Avoidance Presentation and Demonstration
### November 10, 1998 at 0930 Hours
### William J. Hughes Technical Center Hanger
### Conference Room 308

0930 – 1015: Presentation by Robert Severino on his TERRAVOID System

1015 – 1039: Questions and Answers

1130 - 1230: First Demo Flight

1245 - 1330: Second Demo Flight

### Attendees List

| | | | | |
|---|---|---|---|---|
| 1 | Balakirsky, Jay | Orbital/Fairchild Defense | 301-428-6633 | Jayb@oscsystems.com |
| 2 | Biehl, Keith (test pilot) | ACT-370 | 609-485-6480 | keith.biehl@faa.gov |
| 3 | Buckanin, Dot | ACT-300 | 609-485-5016 | dorothy.buckanin@faa.gov |
| 4 | Edmonds, Jack | Hi-Tec Systems | 609-485-8185 | jack.ctr.edmonds@faa.gov |
| 5 | Gaetano, Armando | ACT-370 | 609-485-5895 | armando.gaetano@faa.gov |
| 6 | Ingraham, Mary | Hi-Tec Systems | 609-485-8185 | mary.ctr.Ingraham@faa.gov |
| 7 | Lawrence, David | Pilatus | 303-465-9099 | www.pc12.com |
| 8 | Livack, Gary | AFS-400 | 202-267-7954 | Garrett.livack@faa.gov |
| 9 | McNeil, Michael | ACT-310 | 609-485-4453 | mike.mcneil@faa.gov |
| 10 | Powell, Dick | ATA-100 | 202-267-8790 | Dick.powell@faa.gov |
| 11 | Primeggia, Carmine | AND-470 | 202 493-4710 | carmine.primeggia@faa.dot.gov |
| 12 | Purcell, Paul | MITRE/CAASD | 702 883-7748 | ppurcell@mitre.org |
| 13 | Reichenbach, Patty | AAR-201 | 609-485-4188 | patricia.reichenbach@faa.dot.gov |
| 14 | Sparacino, Peter | AAR-201 | 609-485-5430 | peter.sparacino@faa.gov |
| 15 | Swancy, Howard | AFS-400 | 202-267-8724 | Howard.swancy@faa.gov |
| 16 | Swanseen, Bill | ACT-300 | 609-485-5392 | Swansee@faa.gov |
| 17 | Wong, Gene | AND-470 | 202 267-5339 | gene.wong@faa.dot.gov |
| 18 | Yost, Ralph | ACT-320 | 609-485-5637 | ralph.yost@faa.gov |
| 19 | Zeher, Michael | Orbital/Fairchild Defense | 301-428-6370 | Mzeher@oscsystems.com |

**Figure 42 Agenda for FAA Presentation and Flight Tests**

### D.4.11.3 Acceptance Test Plan

The flight test plan is separated into two dimensions. The first dimension includes the functional description of the Terrain Avoidance operational modes that would be tested during the flight tests. The second dimension includes the waypoint location where each functional mode would be tested.

In terms of the operation modes, the flight test sequence would be as follows:

1) Insure that no warning modes were triggered.
2) Take off as normal.
3) Before reaching 750 feet altitude, gently glide back to a lower altitude. This would trigger the Mode 3-Insufficient Climb after Takeoff.
4) Climb through 750 feet. Insure that the system would automatically transition for "takeoff mode" to "free flight mode."
5) Fly enroute to mountainous area observing slewing maps in tactical display.
6) As mountainous areas are approached, gently dive below 2000 feet, falling greater than 500 feet per minute. Observe Mode 1-Excessive Descent Rate.
7) When mountains are within 30 NM and aircraft if pointing at mountains, observe Mode 4-Terrain Proximity.
8) Turn away from mountains, so that they are no longer within the safety zone. Observe Mode 4 go to "OK" status.
9) Speed up to 450 knots while aimed at mountains. Observe both Mode 4 and Mode 2-Excessive Terrain Closure Rate trigger alerts.
10) Fly back to airport.
11) On final approach, switch to Landing Mode.
12) Vary glideslope below 3 percent. Observe Mode 5-Deviation from Glide Slope alert.
13) Resume 3% glideslope. Observe Mode 5 return to OK status
14) Below 1000 feet, observe altitude callouts every 100 feet down to touchdown.
15) After touchdown, observe all mode return to OK status.

In terms of waypoints flown, the flight test sequence would be as follows:

a) Take off from Hughes Technical Center.
b) From Atlantic City Airport, fly 270 degrees 46 miles to the nuclear power plant cooling tower just west of Canton.
c) Then fly 340 degrees 8 miles up the Delaware River to the C&D canal.
d) Then follow C&D canal 270 degrees 25 miles to Susquehanna River.
e) Then follow River at 330 degrees about 32 miles.
f) Once the terrain avoidance modes are triggered to everyone's satisfaction, return home via the same route.
g) Note that the entire route is on the Washington Section chart, which appears constantly on the Position Integrity tactical display next to the TerrAvoid window.

## D.4.11.4 Equipment and Location

The aircraft used was a new Pilatus PC-12, tail number N210PT . It is shown in front of the FAA Technical Center in the following picture.

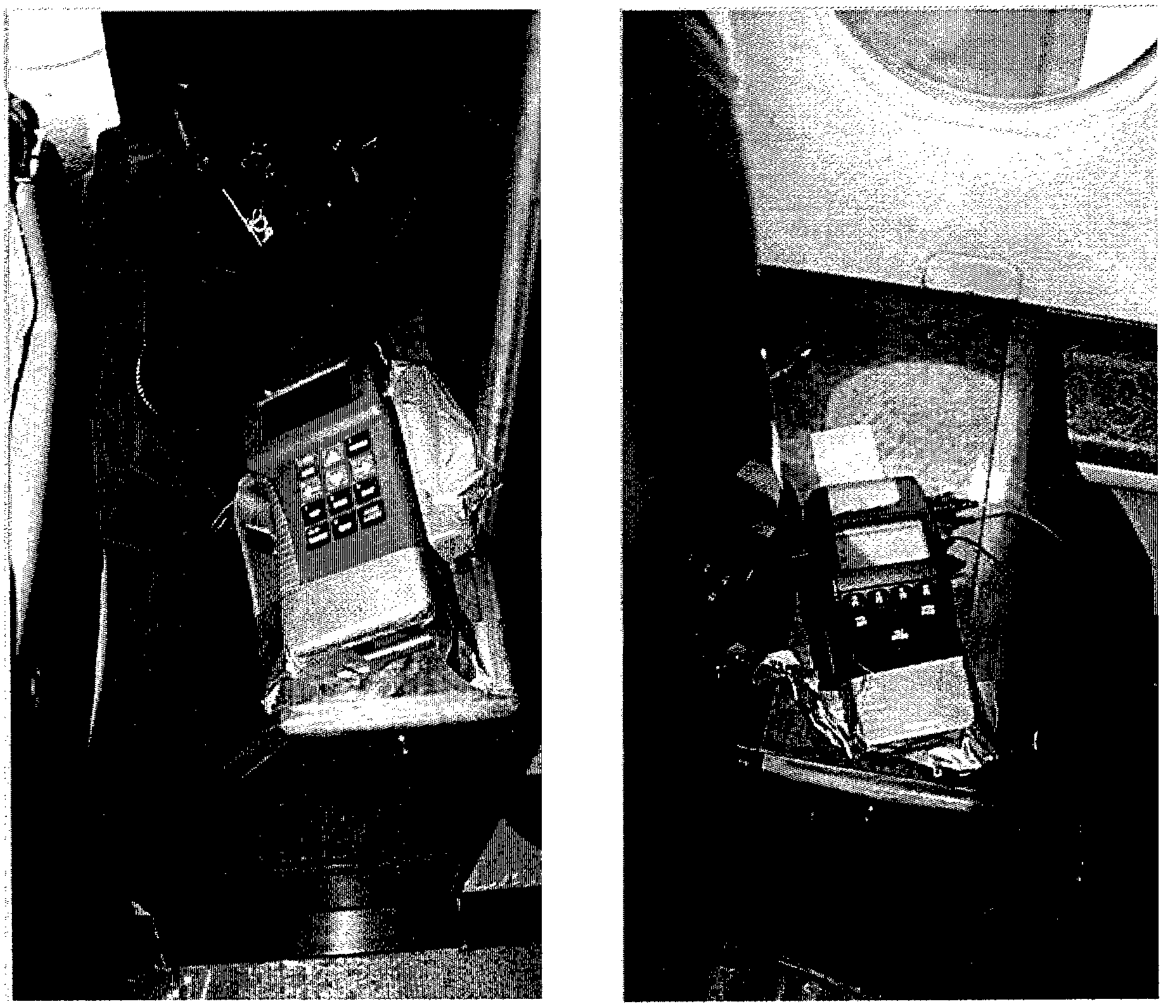
**Figure 43 Pilatus PC-12 at FAA Technical Center**


The two GPS antennas were placed on the dashboard of the cockpit. They are just out of view in the following picture, but were located on the right side, about 12 inches apart.

**Figure 44 PC-12 Cabin with GPS antennas installed in dashboard**

The GPS units were placed just behind the cockpit bulkhead wall. The PLGR was placed on the left side of the aircraft and the SOLGR was placed on the right. Less than 10 feet of cable was used to interface the GPS antennas to the receivers, and less than 6 feet of serial cable was used to interface the receivers to the laptop computers.

**Figure 45 GPS Receiver Placement in PC-12 Cabin**



The Toshiba Tecra 730 (150 MHz) laptop was placed on the left side of the aircraft, while the Toshiba 740 (166MHZ MMX) laptop was placed on the right side.

**Figure 46 Toshiba Laptop placement in PC-12 Cabin**

## D.4.11.5 Participants

Flight Test #1 included (from left to right in the picture below):
1)Dave Lawrence, Pilatus Business Aircraft, 303-465-9099
2)Dot Buckanin, FAA ACT-300, 609-485-5016
3)Bob Severino, Dubbs & Severino, Inc., 949-854-2643
4)Jay Balakirsky, Orbital/Fairchild Defense, 301-428-6633
5)Michael Zeher, Orbital/Fairchild Defense, 301-428-6370
6)Gene Wong, FAA AND-740, 202-267-5339
7)Paul Purcell, MITRE/CAASD, 702-883-7748

For the first flight, our Pilatus pilot was Jed Johnson and our guest pilot was Kieth Biehl, FAA ACT-370, 609-485-6480.

**Figure 47 FAA Participants in Flight Test #1**

On our second flight test the witnesses were (from left to right in the picture below)

1)Ralph Yost, FAA-ACT-320, 609-485-5637
2)Peter Sparacino, FAA-AAR-201, 609-485-5430
3)Armando Gaetano, FAA-ACT-320, 609-485-5895
4)Bob Severino, Dubbs & Severino, Inc., 949-854-2643
5)Jack Edmonds, FAA coordinator from Hi-Tec Systems, 609-485-8185
6)Mary Ingraham, (author of the flight summary) FAA coordinator from Hi-Tec Systems, 609-485-8185
7)Dave Lawrence, Pilatus Business Aircraft, 303-465-9099

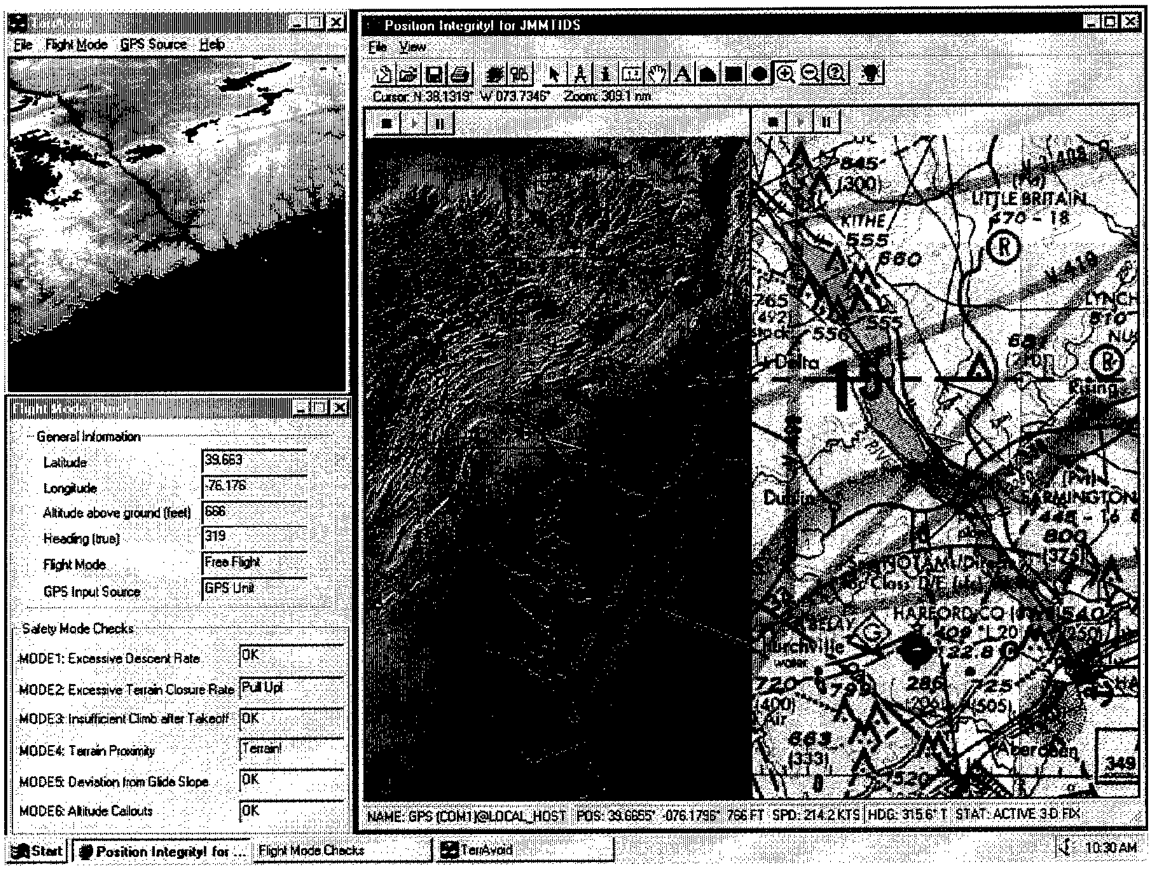
On the second flight, Jed Johnson was our Pilatus pilot and Ralph Yost (#1) was our guest pilot. These two are shown in the cockpit picture on page 8.

**Figure 48 FAA Participants in Flight Test #2**

## D.4.11.6 Results

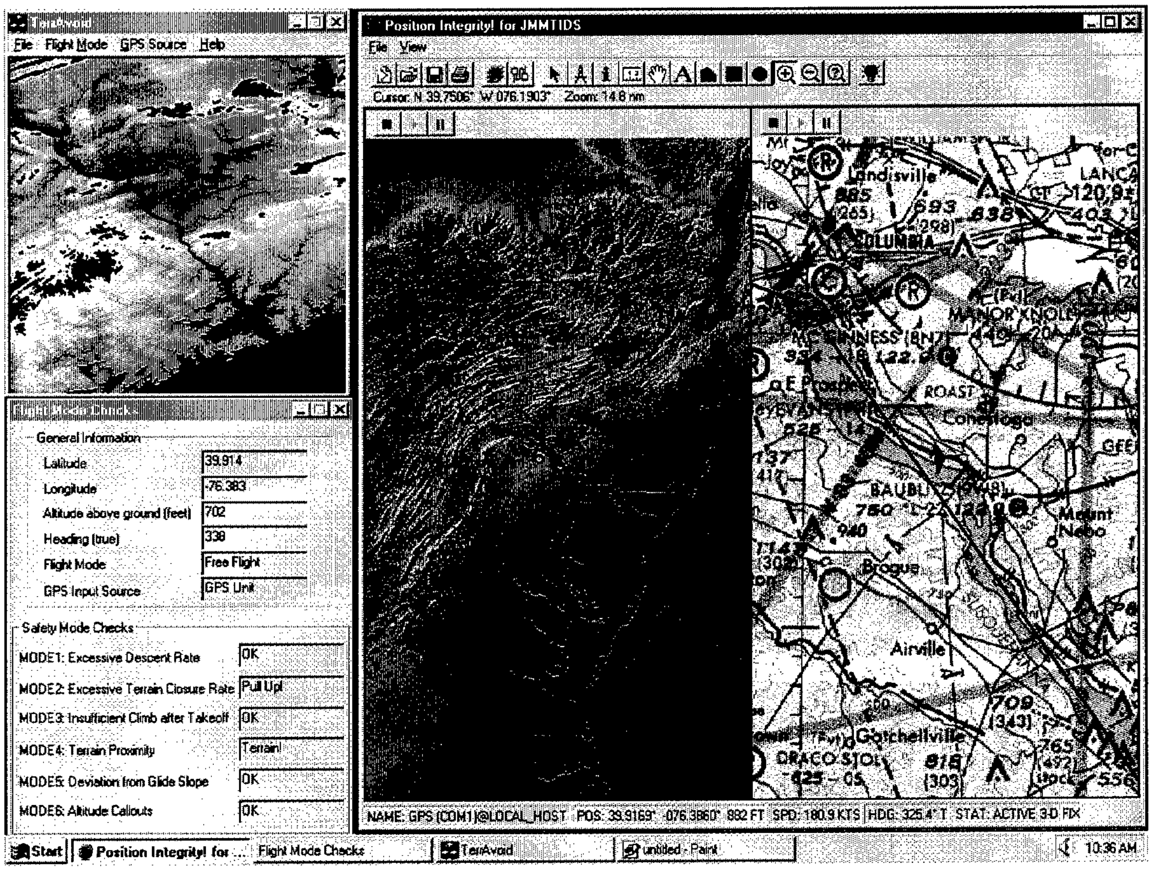
All terrain avoidance modes worked as planned. They alerted when the trigger conditions were present and return to OK status when the trigger condition was removed. Both flight tests were identical in every way and the system was repeatable in all respects. The following screen shot shows our progress as move up the Susquehanna River. Mode 2 is triggered because of our low altitude and Mode 4 is triggered because of the hills on both sides of the river.

**Figure 49 Integrated Display at beginning of Terrain Approach**



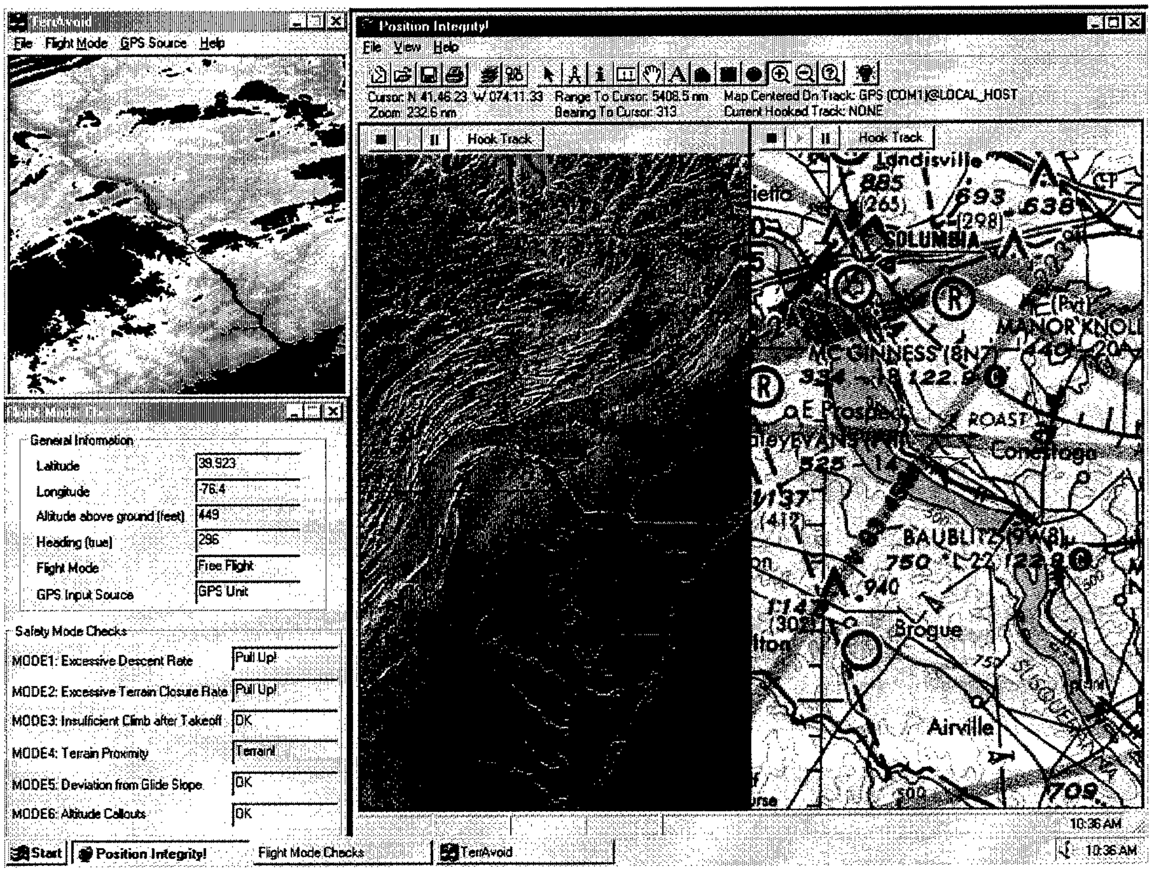
In this second screen shot, the aircraft has moved considerable up the Susquehanna River and the underlying terrain renditions have changed on the TerrAvoid window to show more of the "rippled" mountain ranges just past Harrisburg. The ridgelines are shown as almost vertical bands of deep red.

**Figure 50 Integrated Display with Terrain Warnings**



In this third screen shot we have dropped altitude to less than 500 feet to bring out the deep red mountain coloration of the surrounding hills. This represents the most northerly point we traversed before returning to Atlantic City Airport. Because of the steeply banked elevation-losing turn we instructed the pilot to make, we were also able to trigger Mode 1-descent rate; while Mode 2 and 4 were tracking the dangerous terrain.

**Figure 51 Integrated Display at extreme terrain approach, 449 feet altitude**



## D.4.11.7 Witness Comments

The FAA wrote up the following press release following our successful flight test:

# Briefing and Demonstration of GPS-Based Terrain Avoidance System by Bob Severino

A briefing was held in Conference Room 308 in the Hangar at the William J. Hughes Technical Center on November 10, 1998 at 9:45 AM to demonstrate Dubbs & Severino's GPS-Based Terrain Avoidance System. Mr. Bob Severino came from Irvine, California to demonstrate his company's system; Mr. David Lawrence and two pilots flew a Pilatus PC12, single engine turbo prop from Colorado to give demo flights to interested attendees at the meeting.

The GPS-Based Terrain Avoidance System began as a Small Business Innovation Research project under the Technology Reinvestment Project in 1993 and has since become an Small Business Technology Transfer (STTR) Phase II and Phase III with the US Army and US Navy which is flight testing the system. It is a genuine success story.

This GPS-based terrain avoidance and navigation system is designed to help prevent Controlled Flight into Terrain (CFIT) and improve situational awareness for the pilot. Two software packages "TerrAvoid" and "Position Integrity" combine GPS data with high-resolution maps of the earth's topography. "TerrAvoid" graphically shows pilots if they are flying dangerously close to mountains, while "Position Integrity" is a moving map that details the aircraft's exact position. The terrain avoidance system features a color graphics display of terrain and obstacle data in a 60 nautical mile region around the aircraft, showing the highest elevations in the warmest colors (green-safe, yellow and red -highest). Six terrain avoidance profiles of TSO C92c are used to perform the safety mode checks. The real-time navigation display system provides up to four windows of moving maps, photo-imagery, or shaded relief depictions around the aircraft using a variety of aeronautical geosets provided to users on CD-ROM's. At present the data is based on 100-meter postings. The Egyptian military has incorporated the terrain-avoidance software in unmanned air vehicles. The SOCOM wearable computer uses the software for graphic display and tactical control.

Mr. Severino brings together public access data from the Jet Propulsion Laboratory (JPL), Goddard Space Flight Center and the Geodetic Survey and NIMA. By the end of 1999 and 2000, Dubbs & Severino hope to have higher resolution data working in cooperation with the JPL and shuttle data to build an improved database (30 meter postings for military use). The next step would be to work with an avionics company towards volume, and mass-production to make the terrain avoidance system more cost-effective to lower-end General Aviation.

Two demonstration flights were held on Nov. 10 at 11:30 and 1:30 for those interested. Two laptop computers were used which showed four windows of maps, shaded relief maps, etc., including an oral warning voice. Mr. Severino explained the system as we flew down the Susquehanna River and near the Delaware Bay to locate hilly terrain. It was a highly interesting and informative flight.

### D.4.11.8 Administrator Comments

The following correspondence was sent from Dorothy Buckanin to Robert Severino in response to our thank you letter for the opportunity to demonstrate TerrAvoid at the FAA Technical Center:

X-From_: Dorothy.Buckanin@faa.gov Sun Nov 22 18:52:02 1998
X-Mailer: ccMail Link to SMTP R8.20.00.25
Date: Sun, 22 Nov 1998 21:30:18 -0500
From: "Dorothy Buckanin"<Dorothy.Buckanin@faa.gov>
To: <dubsev@deltanet.com>
Cc: <Michael.McNeil@faa.gov>, <Armando.Gaetano@faa.gov>,
<Michael.McNeil@faa.gov>, <Armando.Gaetano@faa.gov>
Subject: Re: FAA Flight Test

Bob,

Thanks for the great demonstration. Since then, I have had the opportunity to discuss how to get your system certified with our Aircraft Certification experts. We have identified the appropriate contact and a possible way to expedite the certification process if you are interested.

I believe the next step would be to discuss how you want to proceed. Are you interested in allying with a major avionics manufacturer? Have you patented your idea to protect your interests? and a few more questions.

Our General Aviation program and the Safe Flight 21 program have considerable interest in your system. Both are under a tight time schedule so I believe that it would be to your advantage to work with us to pursue this while the iron is hot. I will help to the maximum extent possible.

Dot

_____________________ Reply Separator

_____________________

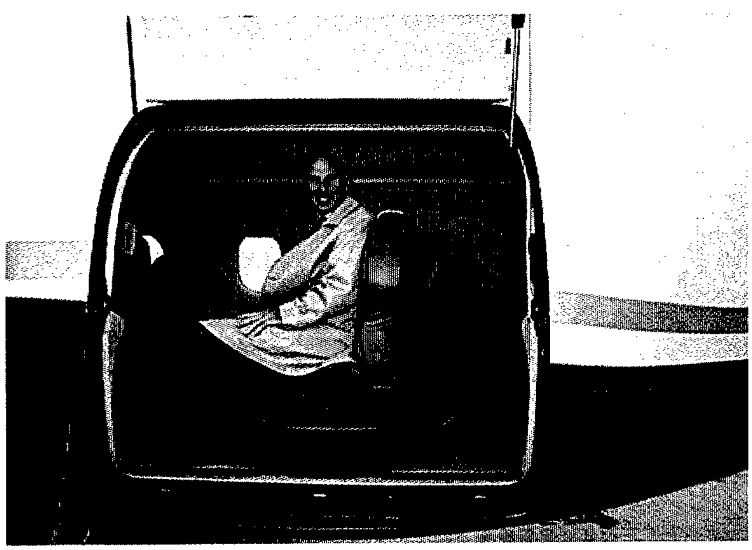
Subject: FAA Flight Test
Author: "Robert A. Severino" <dubsev@deltanet.com> at smtpgate
Date: 11/16/98 9:26 PM

Dot,

Attached is an actual screen shot from our second flight test conducted last Tuesday at the FAA Technical Center in Atlantic City using the multi-mission Pilatus PC-12 aircraft. The TerrAvoid screen in the upper left shows our DTED level 1 image rendering of the increasing terrain slopes as we approached the hills north of Philadelphia. The two Position Integrity tactical display windows highlight the area overflown using USGS shaded relief with NIMA-DAFIF vector aeronautical boundary layers in the center window and MAPTECH digitized Sectional Aeronautical Chart on the right. Thanks to you Jack for your help in managing the logistics for the presentation and demonstrations, and we also want to acknowledge the flight planning assistance on the part of FAA test pilot Keith Biehl. I am also re-attaching Mary Ingraham's excellent summary of the day's activities. From feedback I received from many of the participants, it appears that our technology demonstration objectives were met. My thanks to all at the FAA for making this flight demonstration possible.

Bob Severino
Dubbs & Severino, Inc.
949-854-2643
www.position-integrity.com

**Figure 52 Robert Severino in PC-12 after successful series of flight tests at FAA Technical Center**



# F. BIBLIOGRAPHY

## *F.1 GOVERNMENT DOCUMENTS*

The following documents of the exact issue shown form a part of the specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of the specification, the contents of this specification shall be considered the superseding requirement.


Specifications

---Federal

1. FAA TSO-C92c Airborne Ground Proximity Warning Equipment (3-19-96)
2. RTCA DO-161A Minimum Performance Standards-Airborne Ground Proximity Warning Equipment (May 27, 1976)

---Military

1. MIL-D-89020 (28 May 1993) Digital Terrain Elevation Data (DTED)
2. DMA PM TM 8321.1 (Nov 90) Digital Vertical Obstruction File
3. DMA TR 8350.2 Digital Vertical Obstruction File
4. DMA/GIMA Briefing on DVOF
5. DMA PS/1FD/086, Edition 5, March 1996 Digital Aeronautical Flight Information File-DAFIF


Copies of specifications, standards, drawings, and publications required by suppliers in connection with specified procurement functions should be obtained from the contracting agency or as directed by the contracting officer.

## *F.2 NON-GOVERNMENT DOCUMENTS*

The following documents of the exact issue shown form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be considered a superseding requirement.


Specifications

1) CPN 988-2340-001 Precision Lightweight GPS Receiver (PLGR) Interface Control Document NMEA 0183 (25 August, 1995)
2) TIFF Revision 6.0 (June 3, 1992)
3) GeoTIFF Format Specification Revision 1.0 (November 10, 1995)


Technical society and technical association specifications and standards are generally available for reference from libraries. They are also distributed among technical groups and using Federal Agencies.

## G. APPENDIX A- DEFINITIONS AND GLOSSARY

# ADRG

-ARC Digital Raster Graphics -DMA produced set of navigation charts of all scales.

# AGL

-Above Ground Level, the difference between the aircraft altitude and the terrain height at that horizontal location.

# Army

-Coordination testing was performed for ARMY and U.S. SOCOM (especially JSOC) witnesses. The U.S. Army Research Office was the designated executive sponsor, through the Army STTR Phase II program. Testing includes a combination of fixed and rotory wing flight conduct.

# A/S

-Anti Spoof - The DOD coding of the precise P code GPS signals into an encrypted "Y" code data stream.

# Azimuth

-The horizontal vector originating at ownship's center of gravity.

# C/A Code

-The commercial grade positioning service provided by the GPS service which allows positioning within 100 meters horizontally and 140 meters vertically CEP(90%)-circular error probability.

# CADRG

-Compressed ADRG - DMA's latest series of digitized charts CD-ROMS which have a 55:1 compression factor over the regular digitized ADRG data. The data is stored in the DMA's Raster Product Format.

# CDTED

-Compressed DTED - DMA latest series of terrain data which is compressed an average of 8:1 over the standard DTED product. Lossless Compressed DTED is currently being generated by the DMA. It features an overall compression factor of about 6 to 1 by only providing the first posting in each longitude row with full two byte resolution, and storing the remaining 1200 elevation in the row as a rolling difference in values ("digital pulse code modulation" PCM). The compression is lossless but does require an algorithm to reconstitute the raw data.

# CEP(90%)

-Circular Error Probability - With respect to horizontal accuracy, the true location of a geographic point will lie somewhere within a circle of the specified radius for 90% of the statistically sampled points (2 DRMS) The 3D equivalent is - spherical error probability (SEP).

# CIB

-Controlled Image Base- DMA produced photo-imagery of the world derived from SPOT-Image satellite pictures. The images are in either 5 or 10 meters resolution and stored in NITF format.

# COG

-Course Over Ground, or Track-The actual horizontal azimuth traversed by airplane's center of gravity. May be specified in either magnetic or true degrees. The difference in this area is about 13 degrees.

# DAGR

-Defense Advanced GPS Receiver- the next version of the DOD portable receiver which will follow the PLGR-97 and SOLGR production lines. Due for delivery in the 98/99 timeframe with a production potential of 140,000 units.

# DAFIF

Digital Aeronautical Flight Information File- A NIMA generated database of airport, runway and navaid information that is contains worldwide military facilities as well as FAA and commercial international datasets.

# Datum

-A world geodetic system which provides the basic reference frame and geometric figure of the Earth, models the Earth gravimetrically, and provides the means for relating positions on various local geodetic systems to an Earth-centered, Earth-fixed (ECEF) coordinate system.

# DEM

-Digital Elevation Model-A group of files distributed by the US Geological Survey to represent the natural elevation above ellipsoid for land within the United States.

# DEM Level 3

-The USGS equivalent of the DTED Level I data is the DEM Level 3. Both have 3 arc-second postings and similar accuracy. The DEM are available to the public and a USGS Web site exists for access to all DEMs in the U.S. Each file is about 9 megabyte (versus 3MB per DTED file) possible due to tape format blocks.

# DFAD-Level 3

- Digital Features Analysis Data Level 3 is the DMA's list of all manmade obstacles in the world. This database is being phased out and will be replaced by the new VMAP products. The only unique feature of this dataset is the inclusion of radar reflection data which is not omnidirectional like the VOF, PVOD or VMAP products.

# DGPS

-Differential GPS - A technique of using a fixed reference station to subtract out the satellite clock dithering imposed by the Selective Availability (S/A) degradation imposed on C/A code GPS signals. Current DGPS services are available from: 1) the Coast Guard using Minimum Shift Keying in the 283-325KHz band if you are within 200 nm of a reference receiver (requires radio modem from Trimble, Leica, CSI, or Northstar) , 2) commercial FM broadcast stations using subcarrier formats (98-108 MHz) if you are within 200 nm from an ACCQPOINT and DCI broadcast antenna, 3)direct satellite link using the OMNISTAR/INMARSAT C-band (3750-4250 MHz) available from John Chance (allied with the STARFIX/FUGRO network), or using the Landstar L-band (1573-1576 MHz) from RACAL, or 4) using user radio link and data modems in the FM range from Trimble and Pacific Crest. Also the Wide Area Augmentation System being developed by Hughes Aircraft for the FAA will be online in the 1998 timeframe. Accuracies for all DGPS services are in the 1-5 meters range.

# DMA

-Defense Mapping Agency

# DOF

-Digital Obstacle File - A file maintained by NOS/NOAA which lists all man made obstacles over 500 feet in the US. The file is listed by lat, long, and height.

# DTED

-Digital Terrain Elevation Data-A group of files created by the DOD/DMA to represent the natural elevation above ellipsoid for all land on the surface of the earth. Eight CD-ROMs cover the US. We are in DTED disk 128. Level 1 has 3 arc second posting with around 100 meter spacing. Level 2 is 1" with 30m; level 3 is .3" with 10m, level 4 is .1" with 3 m, and level 5 is .03" with 1m. The new DTED level 0 will include 30 arc-second postings with about 1000 meters between points for world wide coverage, with level 1 data for 50 nm around each of the 450 international airports.

# DTED Level I

-For the ultimate in terrain data accuracy and resolution, this project will use the Defense Mapping Agency (DMA) Digital Terrain Elevation Data (DTED) Level I, which has elevation postings every 100 meters (3 arc seconds), and an absolute vertical accuracy specification of less than 30 meters (90% Linear Error, Mean Sea Level geoid.) The 3 arc second spacing is only valid from 50 degrees south latitude to 50 degrees north latitude; however this is the primary area of interest. These data are referenced horizontally to the World Geodetic System (WGS 84 ellipsoid.) The DMA distributes these data on standard ISO 9660 CD-ROMs. The elevation data are grouped into files, each of which contains data from a 1 degree latitude by 1 degree longitude section of the world.

DTED Level I data are available for most of the world. To digitize the land-covered area of the earth, approximately 12,800 square meters are required. At a resolution of 100 meter postings, this would consume about 12 Gigabytes. Assuming an overall compression ratio of 6:1 (as is being demonstrated on the Compressed DTED or CDTED project), the total required storage capacity for the whole of the land-covered part of the world with 100 meter resolution is 2 Gigabytes. This could easily fit on 4 CD-ROM disks or 1 magneto-optical disks.

The DTED disk used for Phase I of this project was DMA Stock No. TCD DTED128, PCN CDRM 100028, Edition 2, Date: 16 June 1993, Minimum Bounding Rectangle Area of Coverage: 30 to 42 degrees North, 180 to 108 degrees West. Military Standard MIL-D-89020 (28 May 1993) describes the DTED data formats and protocols. The attached 5 page description is a more concise description of the DTED disk used on this project, and can be found as a "READ.ME" file on the disk.

For Phase I we used the file W118\N33.DT1 which has the Level I data for the 1 degree by 1 degree cell whose southwest corner is 118 degrees West longitude, 33 degrees North latitude. Within this file are 1201 data records, where each data record is all 1201 latitude values with 1 longitude column. The first data record is the left most longitude column (highest West value) and the last data record is the right most longitude column (lowest west value.) The highest and lowest longitudes fall on the 1 degree boundaries.

Within each data record (longitude column) are 1201 latitude values with the first being the lowest latitude (southern most) and the last being the highest latitude (northern most.)

Before a phase I mission only one DTED cell is read from the CD-ROM onto the hard disk, and is then transferred to RAMDISK for faster access. This represented about 3 megabytes. The above formula is used to access each point in the safety cone in real-time. For Phase II, entire CDs will be available for global flight. As the pilot approaches the boundary of one CD, prompts will be cued to request insertion of the next CD required.

# DTED Level II

-Similar to DTED level I, however the posting spacing is 1 arc-second, which approximately 30 meters close to the equator.

# Elevation

- On this project, the height above Mean Sea Level geoid

# Ellipsoid

- revolution of ellipse; ellipsoid heights. The current worldwide ellipsoid is WGS-84. This provides geodetic coordinates (latitude, longitude, ellipsoid heights). GPS receivers output and DMA DTED is reference to altitude in Mean Sea Level.

# GAIMS

-General Aviation Information Management System - A robust, commercial flight computer software architecture being developed by Seagull Technology of Cupertino, CA

# Geoid

-Equipotential surface at sea level; constant gravity potential; orthometric heights. The NAD 27 datum uses a geoid as its reference surface. The altitudes are all above mean sea level (MSL). At our location the geoid MSL altitude is 34 meters higher than the WGS-84 ellipsoid. In some parts of the world, geoid undulations can be as great as +/- 100 meters with respect to an ellipsoid. GPS front panels typically show altitude MSL.

# GEOTIFF

-A group of industry-standard tag sets for the management of georeference or geocoded raster imagery using Aldus-Adobe's public domain Tagged-Image File Format (TIFF). Written and pioneered by Niles Ritter at JPL. The GEOTIFF 1.0 specification defines a set of TIFF tags provided to describe all "Cartographic" information associated with TIFF imagery that originates from satellite imaging systems, scanned aerial photography, scanned maps, digital elevation models, or as a result of geographic analyses. Its aim is to allow means for tying a raster image to a known model space or map projection, and for describing those projections.

# Glideslope

-The angle of incidence (or inclination" an airplane makes on its approach to a landing strip. Visual Approach Slope Indicators(VASI) and Precision Approach Path Indicators (PAPI) are a group of red, amber and green lights which direct the pilot to an ideal glideslope. The ideal glideslope is 3 degrees. "Low" is less than 2.5; "slightly low" is around 2.8; "slightly high" is around 3.2; and "high" is more than 3.5 degrees.

# GNC

-Global Navigation and Planning Chart - DMA produced chart at a scale of 1:5,000,000. There are approximately 50 in the set for the world. Other than for the polar regions, the charts use Lambert Conformal Conic projection. We are in "GNC 2"

# GPS

-Global Positioning System - The DOD positioning and navigation system consisting of 24 satellites orbiting asynchronously about the earth, which provide continuous fixes in position, velocity and time to users anywhere between the earth's surface and the ionosphere.

# GPS-ICD-153

- The Rockwell developed/ DOD GPS Joint Program Office approved interface protocol used by the PLGR and to be used by the SOLGR and DAGR.

# GPS Status

-The different modes representing the availability and accuracy of the navigation information. The modes are 1)GPS unavailable, 2) Time only (1 satellite), 3) C/A 2D (3 sats), 4) C/A 3D (4 sats), 5) DGPS, 6) P(Y) 2D (3 sats), 7) P(Y) 3D (4 sats), 8) P(Y) WAGE, 9) SDGPS. The modes are not mutually exclusive.

# Heading

-The azimuth that the airplane nose is pointed at. The difference between the track (or course over ground) and the heading is due to the wind and is termed the "crab angle"

# HOL

- High Order Language

# IFR

- Instrument Flight Rules - The FAA mandated set of procedures for a pilot to follow when visibility is so low that terrain and traffic would be seriously obscured.

# IFSAR

-Interferometric Synthetic Aperture Radar - the technique pioneered by JPL for determining the terrain features of other planets. Now being applied by the SRTM program to map the earth.

# IOD

-Interferometric Obstruction Data- obstacles above natural terrain height as derived from the NASA/JPL Shuttle Radar Topography Mapper.

# ITHD

-Interferometric Terrain Height Data - DTED derived from the NASA/JPL Shuttle Radar Topography Mapper with an absolute accuracy of 16 meters and a relative accuracy of 8 meters.

# ITHD Level II

-A NASA shuttle mission will carry an interferometric radar to scan the earth's surface at 1 arc second or 10 meters resolution (with about the same accuracy).

# JFIF

-JPEG File Interchange Format is a minimal file format which enables JPEG bitstreams to be exchanged between a wide variety of platforms and applications.

# JPEG

-Joint Photographic Experts Group- a toolkit of ISO/CCITT standards for continuous tone image compression (both color and greyscale). Compression algorithms fall into either lossy or lossless categories. Discrete Cosine Transform base algorithms are lossy, while spatial-prediction algorithms based upon a two-dimensional Differential Pulse Code Modulation (DCPM) techniques or entropy encoding are lossless. JPEG provides for three levels of lossy compression which roughly correspond to whatever frequency content has the highest energy content. JPEG provides for use of entropy encoding with either Variable Length Codes (commonly known as Huffman encoding) or with Arithmetic entropy encoding models( which are proprietary to ABM and AT&T). JPEG decompression senses the compression scheme and parameters used and automatically initialized.

# JPL

-Jet Propulsion Laboratory, specifically the Cartographic Application Group within the Image Processing Lab, who is our subcontractor.

# JNC

-Jet Navigation Chart - DMA produced chart at a scale of 1:2,000,000. There are approximately 125 in the set for the world. Other than the charts for the polar regions, the Lambert Conformal Conic projection is used. We are in "JNC 43"

# JOG-A

- Joint Operations Graphic-Air - DMA produced chart at a scale of 1:250,000. There are approximately 500 in the set for the world. Linear projection is used. We are in "NI 11-8, Santa Ana".

## Lambert Conformal Polyconic projection

- A chart projection which assumes that the earth is the shape of two cones connected at their base, which forms the earth's equator.

## Latitude

-Horizontal lines which are all parallel to the earth's equator, which is at zero. We are at 34 degrees north latitude, generally referred to in georeferenced graphic packages as "+34". Southern latitudes are usually negative.

## LEO

-Low Earth Orbit, referring to satellite communication systems which orbit a network of vehicles in the 775-2000 kilometer altitude region. Little LEO refers to companies like Orbital Sciences ORBCOMM with a planned 26 satellites. Big LEO refer to large programs like Lockheed/McCaw/Microsoft TELEDESIC which will have 860 satellites.

## Longitude

- Vertical lines which span between the earth's poles. Zero is at Greenwich, England. We are in 117 degrees west longitude, generally referred to in georeferenced graphic packages as "-117". Eastern longitudes are generally positive.

## MSL

-Mean Sea Level - The altitude with respect to a rough geoid standard. Geoids have equipotential surface at sea level and constant gravity potential; MSL altitudes are based on orthometric heights. The NAD 27 datum uses a geoid as its reference surface. The geoid altitudes are all above mean sea level (MSL). At our location the geoid MSL altitude is 34 meters higher than the WGS-84 ellipsoid. GPS front panels typically show altitude MSL.

## Navy

-All references to Navy indicate our SBIR Phase II project with the Naval Air Warfare Center-Warminster, PA for application on the Navy/Marine/SOCOM V-22 Osprey aircraft and other military vehicles.

## NITF

-National Imagery Transmission Format - the raster format used by the DMA to represent CIB and other photo-imagery products.

## NM

-Nautical Mile - 6076.10 feet or the distance represented by exactly 1 arc- minute on the earth's surface at the equator.

## NOAA

-National Oceanic and Atmospheric Administration.

## NOS

-National Ocean Service-The producer of aeronautical charts for commercial and general aviation pilots. NOS is a division of the National Oceanic and Atmospheric Administration (NOAA), which is part of the US. Department of Commerce

## ONC

-Operational Navigation Chart - DMA produced chart at a scale of 1:1,000,000. There are approximately 250 in the set for the world. We are in "ONC G-18"

## PPS

-Precise Positioning Service - which uses P(Y) code signals as opposed to SPS which uses C/A code..

## P(Y)

-The precise GPS code signals which allow positioning within 4 meters. This requires a cryptokey issued by the GPS Joint Program Office under the guidelines established by the National Security Agency. Cryptokeys are issued sixfold in the older KYK-13 format (requiring a KOI-18 paper tape reader) or 100-fold in the newer all-electronic DTD format.

## Photo-Imagery

- Pictures taken in the plan view at granularities close to map scales

## Pitch

-rotation of a vehicle about its left-right horizontal axis.

## PLGR

- Portable Lightweight GPS Receiver - The current generation DOD mobile position device. A production is expected of about 90,000 units, with 50,000 already in the field. The version are PLGR (1993), E-PLGR(94), PLGR-95, and PLGR-96. The enhanced variant E-PLGR added more memory capability; PLGR-95 added RTCM-104 DGPS in C/A code mode; while PLGR-96 adds NMEA-183B output, WAGE, and SDGPS.

## PVOD

-Probabilistic Vertical Obstruction Data - the DMA dataset which uses predictive algorithms to determine the probable location of obstacles to airborne navigation using source material from a variety of national technical means. The dataset is classified.

# Pseudo Color Shaded Relief

- A morphed graphic image which combines a shaded relief map generated from a DTED file, which has then been colorized with increasing height bands indicating a different (usually brighter, more noticeable) color

# RPF

-Raster Product Format - The DMA standard for the storage of CADRG and other raster maps and imagery.

# RAM

-Random Access Memory

# Roll

- rotation of a vehicle about its fuselage axis

# S/A

- Selective Availability - The DOD dithering of the GPS navigation signals to prevent accuracies greater than 100 meters horizontally and 140 meters vertically CEP

# SAC

-Sectional Aeronautical Chart - NOS produced chart at a scale of 1:500,000. These are primarily designed for VFR fight. There are approximately 54 in the set for the US, with each being revised semi-annually. Lambert Conformal Conic Projection is used. We are in the "Los Angeles" SAC

# SDGPS

- Secure Differential GPS - A relatively new technique to combine DGPS to add further accuracy to P(Y) code encrypted signals. The accuracies are about 1 meter kinematic (on the move) even in the presence of strong solar flare, like the solar max expected in 2000. Will probably involve the distribution/transmission of pseudo-range corrections to the P(Y) code signals, as opposed to applying C/A code pseudo-range corrections.

# Slant Range

-A distance from the aircraft to a desired destination waypoint or target which takes into account the vertical difference in height. It is the 3D range, which is often underestimated on 2D moving map displays.

# SLGR

-Small Lightweight GPS Receiver. The military ruggedized 6- channel unit which was produced by Trimble from their Trimpak product line to support the US. troops in Desert Storm. Some supported PPS but most just used C/A code.

# SOG

-Speed over ground. A scalar of velocity which only accounts for the horizontal component of the flight vector. May be used as a rough proxy for airspeed, if aircraft velocity is high with respect to wind flow..

# SOLGR

−The next generation DOD P(Y) code GPS receiver designed for the Special Forces. A production lot of 2500 is expected for this underwater/harsh environment variant. A follow on to the PLGR family with many of the same peripherals and interface protocols. Will add L2 to the PLGR spec. Will still use the GPS-ICD-153 interface protocol.

# SPS

-Standard Positioning Service - use of C/A code as opposed to PPS, which uses P(Y) code.

# SRTM

-Shuttle Radar Topographic Mapper - The NASA/JPL mission in 1998 which will map the earth's surface yielding DTED level 1 and level 2 postings, but at much finer vertical accuracy. This will be called Interferometric Terrain Height Data (ITHD). Other products include Interferometric Obstruction Data (IOD), and Land Cover Images at better than 1:100,000 scale.. Paid for by the DOD.

# SuperChart

-The NOS collection of all continental US SAC's with the baseline meridian longitude at Texas. On the SuperChart, therefore, Western SAC's slopes up and to the right, while Eastern SAC slope to the left. Used by the FAA Advanced Automation System displays at the regional air traffic control centers. .

# TAC

- VFR Terminal Area Chart - NOS produced chart at a scale of 1:250,000. These are only available for the most popular airport regions. The charts depict the so called "Class B" (formerly TCA) air space which surrounds most major airports like LAX, the "Class C" (formerly ARSA) air space which surround minor airports like Orange County, the "Class D" (formerly TSRA) air space like the off-shore El Toro Marine Base approach, Restricted areas like Camp Pendleton, and Military Operations Areas (MOA) like Edwards AFB supersonic corridor north of Mojave. There are approximately 28 in the set for the US., with each being revised semi-annually. Lambert Conformal Conic Projection is used. We are in the "Los Angeles" TAC

# TIFF

-Tagged Image File Format - The digital format for storing raster graphic data which was developed by the Aldus Corporation and is in the public domain. The latest version 6.0 includes the cartographic tag extensions developed by the Jet Propulsion Laboratory, which allow the storage and retrieval of cartographic data (lat and long) from within the image file itself.

# TLM

-Topographic Line Maps - DMA produced charts at a scale of 1:50,000 which depict regions about the size of large cities.

# TPC

-Tactical Pilotage Chart - DMA produced chart at a scale of 1:500,000. There are approximately 500 in the set for the world. Linear projection is used. We are in "TPC G-18C"
Track, or course over ground-The actual azimuth traversed by airplane's center of gravity.

# VFR

-Visual Flight Rules - The FAA allowed set of procedures which can occur when the pilot has good visibility of terrain and traffic.

# VMAP

-Vector Smart Map - the new DMA series of layered vector products which will eventually include all data currently shown in raster format. VMAP-level 0 will include information normally found on 1:1,000,000 scale raster maps, while level 1 will cover roughly 1:250,000 scale.

# VMAP-AD

-VMAP-Aeronautical Data - DMA's level-less version of it vector data set designed for pilots. Obstacle data is included in several of the layers, along with max terrain elevations by region, and approach and en-route information..

# VOF

-Vertical Obstruction File - a database of all obstructions to aircraft in the world, maintained by the DMA. Not a standard release product.

# WAC

-World Aeronautical Chart-NOS produced chart at a scale of 1:1,000,000. There are approximately 21 in the set for the US, which are revised annually. Lambert Conformal Conic Projection is used. We are in "CG-18"

# WAGE

-Wide Area GPS Enhancement- the use by military receivers of the ionospheric corrections which are broadcasts in the P(Y) code datastream. The net effect is to reduce military accuracies from 16 meters to 4 meters without the need for sampling the L2 frequency to determine the errors introduced by the atmosphere.

# WGS-84

- The world-wide horizontal datum to which GPS positions are referenced.

# Yaw

- Rotation about a vertical axis through the center of the vehicle.

# REPORT DOCUMENTATION PAGE

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13. ABSTRACT *(Maximum 200 words)*

The U.S. Military has a need for a covert (non-emitting) system that will assist the pilot to navigate using terrain following techniques while maintaining maximum safety against terrain impact. This project addresses the software development and system integration of a GPS-Based terrain avoidance system. The system extrapolates the region immediately ahead of the aircraft and alerts the pilot when the current flight vector intercepts the safety margins surrounding upcoming terrain obstacles. The system performs its task using a set of proprietary "Adaptive Real-time Altitude Detection" (ARAD) algorithms. These compare the present GPS-derived aircraft latitude, longitude, and elevation above sea level, with the NIMA DTED data for the same location. The ARAD algorithms extrapolate ahead of the current position, giving the pilot adequate time to take evasive action in avoiding upcoming terrain. The pilot can view his current location on a laptop computer that displays topographical and military aeronautical charts, as well as photo-imagery and shaded relief depictions. The final product is called "TerrAvoid" and runs on a COTS laptop computer using the Microsoft Windows NT operating system. A multi-window moving map application is also integrated.

14. SUBJECT TERMS

| | | | |
|---|---|---|---|
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| Moving Map | GeoTIFF | CFIT | Safety |

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